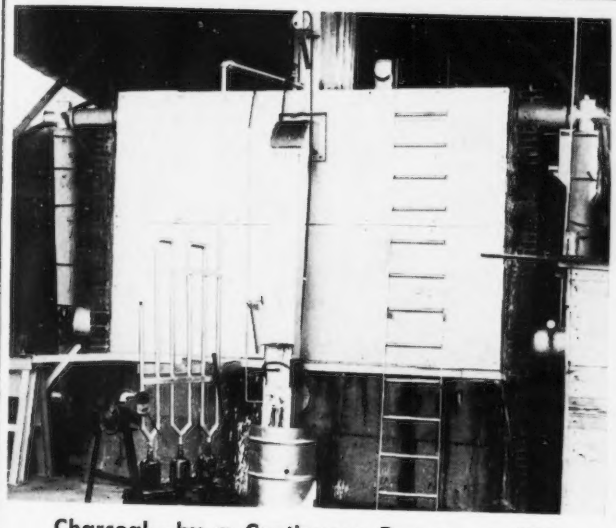
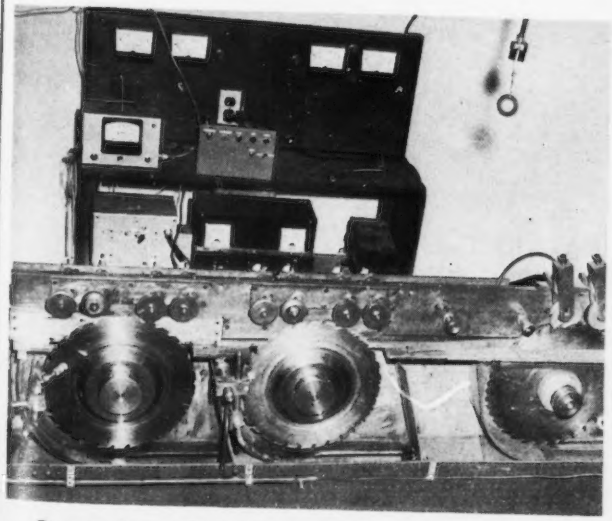
Forest Products Journal

THIS ISSUE—
NON-DESTRUCTIVE TESTING

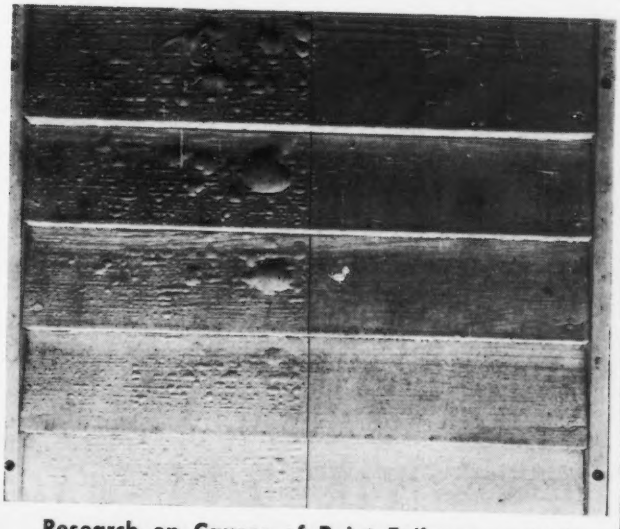


Charcoal—by a Continuous Process, p. 395

Drying Chemically Treated Lumber, p. 398



Research on Thin Circular Saw Blades, p. 404



Research on Causes of Paint Failures, p. 417

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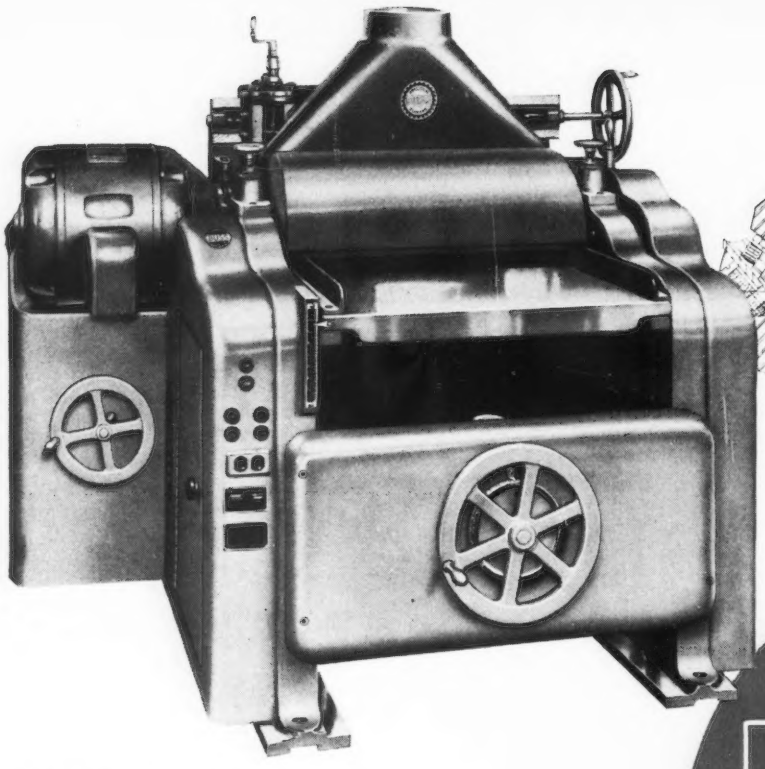

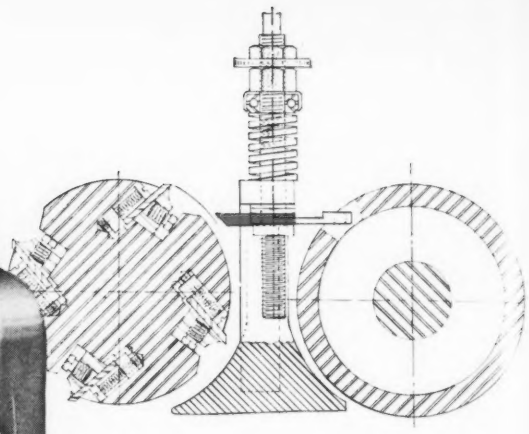

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FOREST PRODUCTS JOURNAL

Vol. IX, No. 11 November, 1959

CONTENTS

Page

CHARCOAL

Progress in Charcoal Production—Continuous Residue Carbonization .... *E. E. Dargan and W. R. Smith* 395
Sawdust conveyed by screw feeds is carbonized in two hours with no supplemental heat added after carbonization is started.

WOOD DRYING

Kiln Drying Chemically Treated Scarlet Oak and White Oak Lumber .... *A. E. Lund and M. A. Taras* 398
Lumber treated by two different methods was dried rapidly at high temperatures.

Wood Moisture Content in Homes—Seasonal Variations in the Southeast .... *P. J. Bois* 427
In cooperation with kiln clubs, the author investigated moisture content variation in both the mountain and piedmont areas.

MACHINING

Improvements through Research on Thin Circular Sawblades .... *C. P. Berolzheimer and C. H. Best* 404
A presentation of theory and practices that result in a 10-percent increase in the final product.

NON-DESTRUCTIVE TESTING

Indices of Quality—Vibrational Properties of Wood ..... *B. A. Jayne* 413
The author presents a method of non-destructive testing that results in pin-point estimations of the characteristics of clear wood.

PAINT

Understanding the Mechanisms of Deterioration of House Paint .. *F. L. Browne* 417
Checking, crumbling, curling, flaking, and alligatoring are examples of chemical deterioration of house paint generally caused by water in conjunction with ultra violet light.

GLUES AND GLUING

Adhesives for Dissimilar Materials ..... *C. L. Carlson* 431
Discussion on the more frequently encountered bonding problems caused by chemical and physical dissimilarities of bonded members.

EDUCATION

The Cincinnati Plan: Co-Operative Education ..... *R. A. Van Wye* 434
The co-op plan benefits the university, the employer, and the student.

DEPARTMENTS

FPRS News Digest 3-A

Employment Service 6-A

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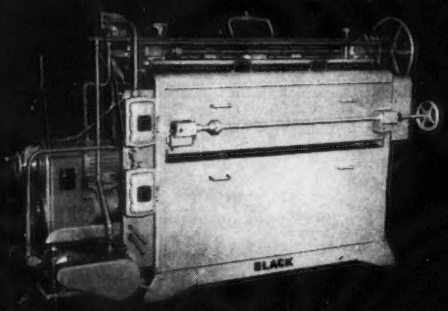

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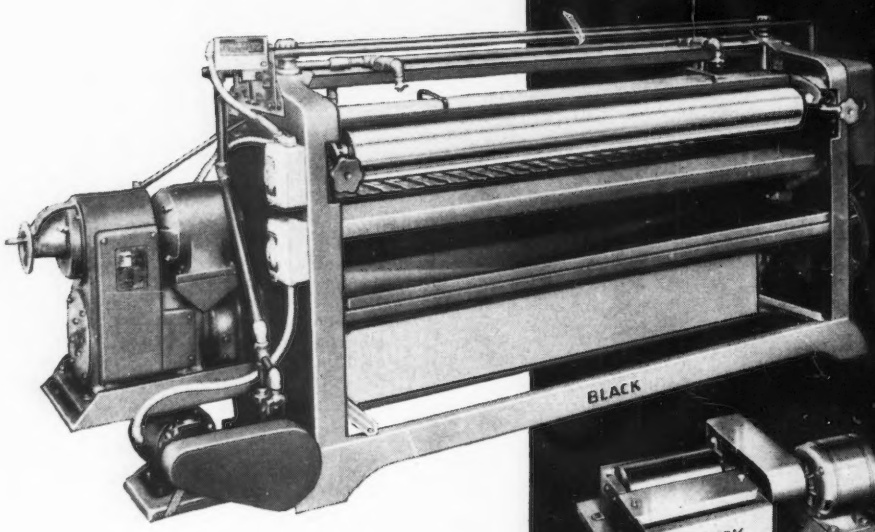

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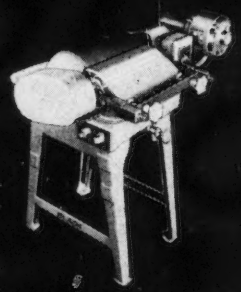

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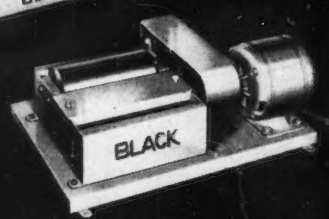

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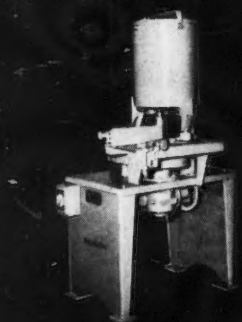

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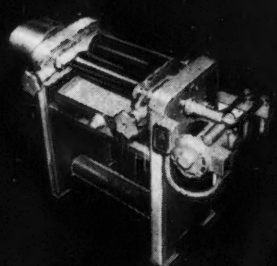

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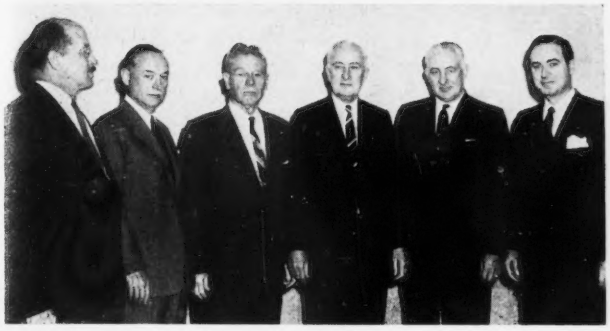
Important FPRS Dates

January, 1960: FPRS National Executive Board, Chicago, Ill.
February 8–9, 1960: Northwestern Section Meeting, Bellingham, Wash.
March 24–25, 1960: Northeastern Section Meeting, Hartford, Conn.
June 5–9, 1960: Fourteenth National Meeting, Montreal, Canada.

FPRS News-Digest

NLMA Spurs Wood Promotion; Enlists FPRS Aid in "Careers Program"



WASHINGTON, Nov.—NLMA elects officers for coming year: Henry Bahr, treasurer; N. Floyd McGowin, chairman, Policy; A. B. Hood, 1st v.p.; Thomas J. McHugh, president; R. M. Ingram, board chairman; and Mortimer B. Doyle, exec. v.p.

NOTED SPEAKERS included, Dr. Ralph Robey, NAM economist; Julian Zimmerman, FHA commissioner; Henry Hill, prominent architect; and Donald Paarlberg, special assistant to President Eisenhower.

NLMA directors moved to increase public acceptance and understanding of lumber industry grade marks by approving resolutions which:

(1) Urged the Federal Housing Administration and private lending agencies to require grade marking of all board and framing lumber used in home construction backed by FHA and other mortgage guarantees. This supported a later announcement by FHA Commissioner Julian Zimmerman that all board and framing lumber used in FHA-insured housing must be grade marked, effective April 1.

(2) Established a special NLMA committee to study possible simplification and standardization of grade designations.

(3) Urged that in establishing programs for management of federally-owned commercial forest land, priority be given to programs and activities to put the administration of such lands on an "income-producing and pay-as-you-go basis."

(4) Asked NLMA's 17 federated associations to provide the U. S. Forest Products Laboratory with detailed information on the market potential for glues in the lumber industry.

(5) Called for immediate preparation of a handbook or design manual on industrial use of lumber, responsible for about one-third of present lumber output.

(6) Ordered an intensification of NLMA efforts in cooperation with FPRS to publicize career opportunities in the private forest industries.

(7) Called for legislation to eliminate false labeling and false advertising of imitation wood products.

National Wood Promotion Program

To step up the tempo and increase effectiveness of the lumber industry's year-old National Wood Promotion Program, the Board approved a 1960 budget of $1,363,424—21% above the $1,130,000 allocated for 1959. This will permit an expansion of all phases of the NWPP—advertising, merchandising, product publicity, technical promotion and intra-industry cooperation work.

Meeting Speakers

Ingram told the meeting that product improvement and better sales and distribution methods hold the key to greater markets for lumber and wood products. He said the lumber industry must match in marketing the progress it has made in forest management and increased log utilization.

Robey said that business prospects appear "good," at least for the first half of 1960. Such conditions, he asserted, can continue "almost indefinitely" and the nation can achieve prosperity "greater than any we have ever experienced"—provided the government and private industry solve certain major problems, including the current steel dispute, the dangers of inflation and the need for additional labor legislation.

Zimmerman also urged the lumber industry to improve its sales and promotional activities, to take advantage of the growing market potential in home construction between now and the year 2000. Zimmerman predicted that the nation's housing inventory will more than double in the next 40 years. New home starts, he forecast, will rise from an annual rate of about 1.35 million at present to an unprecedented 2.25 to 2.5 million units annually by the year 2000.

FPRS EXECUTIVE BOARD met in Chicago, Nov. 4, 5 to discuss 1959 finances and 1960 budget; an expanded publications program; and the technical program and arrangements for the June, 1960 Montreal

International meeting. L. to r. are Col. Jenkins, Ottawa; Fred Dickinson, Calif.; Walt Smith, Asheville; pres. Scotty Harrar; Sec. Frank Rovsek; Joe Allegretti, Chicago; Don Saunders, Maine; Tony Veazey, Butte; and Jim Love, Texas.

NLMA Meeting; FPRS Cooperation, Contd.

Wood has "a living quality that is shared with delight and understanding by all mankind" but architects lack the technical information necessary to take full advantage of its versatility, Hill declared. The San Francisco designer called on lumber manufacturers to increase their output of printed material on wood's special properties, so architects can give the material a new and greater-than-ever role in home design.

Paarlberg said the lumber and housing industries have a definite stake in Administration policies designed to hold down inflation and keep credit from becoming "superabundant." A flood of credit, Paarlberg maintained, would "feed the fires of inflation and create more problems for the housing business than it could possibly solve."

Report of NLMA Special Committee on Education

The Special Committee on Education chairmaned by Ray Berry met on November 11, 1959, with the President, Executive Secretary, and two other members of the Forest Products Research Society as visitors. Discussion of the cooperative efforts to date led to the conclusion that joint goals are not being met because each of the organizations is waiting for the other to initiate atcion. The Committee then recommended to the Board of Directors the adoption of the following resolution:

> "The staff consult with the local area leaders appointed by the Forest Products Research Society and develop a definite grass-roots program in the 14 FPRS Section areas which would distribute the booklet, 'Opportunities Unlimited' as part of the programs."

A question as to the extent of distribution of the publications, "Opportunities Unlimited" and "There is a Challenging Place for You in the New Age of Wood" was discussed by the Committee which recommended that

> "The present procedure for distributing copies of the two NLMA career guidance publications be continued."

A staff recommendation regarding participation in elementary and high school career day programs and in college lectures and seminars led to adoption of the following resolution:

> "NLMA staff members and members of the Industry are urged to participate in elementary and high school career day programs and in college lectures and seminars whenever possible in broad effort to acquaint the public with the 'story of wood' and to stimulate general interest in vocational as well as professional careers in the lumber and wood products industry."

MEETINGS

Pacific Northwest Section to Meet Feb. 8, 9

The next meeting of the Pacific Northwest Section will be held at the Doric Bellingham Motor Hotel in Bellingham, Washington on February 8 and 9, 1960.

One technical session at this meeting will be devoted to plywood manufacture; the other will have a general theme. Papers have been promised regarding the heating of Douglas fir peeler logs, the influence of oil-fired drier temperatures on the quality of cold pressed plywood, simplified data handling techniques, and the permeability of Douglas fir. Field trips to wood using industries in the Bellingham area and other local arrangements are being handled by E. W. Wellwood.

The banquet speaker will be R. J. Seidl of the Simpson Timber Company, who will present an illustrated talk concerning his recent 30-day tour of Russian forest products industries.

Home-Building Short Course

Good design and construction *can* be incorporated into houses built to rent or sell to low-income groups, insists the University of Illinois Small Homes Council. Guidelines for building good minimum-cost housing will be presented at the 15th Annual Short Course in Residential Construction January 14, 15, 1960. Demonstration will be made of a new SHC-BRC nail-glued header designed for 8- to 12-foot spans.

Registration fee of $15 includes tuition, field trip to housing research activities, annual dinner, and publications distributed as part of the course. Registration requests and check should be mailed to the Short Course Supervisor, Division of University Extension, Room 116b, Illini Hall, Champaign, Illinois.

275 Attend North-Central Meeting, Nov. 5, 6

REGISTRATION AREA at successful Region meeting which combined four FPRS Sections.

JACK KOELLISCH, Wood & Wood Products, and DON LUBECK, Hammond Organ Co., who conceived "Factory Finishing" program.

NEW MEMBER John Black, U. S. Forest Products Lab., Walt Smith, Exec. Board, and Ken Kimball, Midwest treasurer exchange good fellowship.

MEETING CHAIRMAN, Joe Allegretti congratulates new supporting member Alec Block, Merit Products Co., L.A., as sec. Rovsek looks on.

PART OF ALL-STAR LINEUP of speakers includes, program chairman Don Lubeck; exec. Carborundum Co.; Steve Blake and Harvey Bennett, Behr-Manning Corp.; exec. Minnesota Mining & Mfg. Co.

FPRS WOOD COMPOSITION BOARD DIV., chairmanned by Jim Roberts (far right) holds local meeting in Chicago to discuss subject of Particle Board Standards. L. to r. A. Briggs, Muskegon; John Black U.S.F.P.L.; Len Ropella and Bill Roddis, Roddis Plywood; and Robert

NEW MEMBERS IN MONTH OF NOVEMBER

Section Officers Please Take Note. Starting this month we are going to publish each month all of the NEW or Transferred-into-the-Section Members. Please adjust your records, and gear to the most concerted New Membership Activity in FPRS history!

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UPPER MISSISSIPPI VALLEY

Vernon W. Meyer, 7447 V, Box 1127, Bottineau, North Dakota

NEW PUBLICATIONS

U. S. Forest Products Lab Publications

Two new reports relating to sandwich construction and design are among the seven new or revised reports recently issued by the U. S. Forest Products Laboratory, Madison. Single copies free upon request.

"Structural Sandwich Design Criteria," Report 2161, presents basic design philosophy for structural sandwich construction under various types of loading. Report 2165, "Long-Term Case Study of Sandwich Panel Construction in FPL Experimental Unit," describes the 12-year exposure and service data that was compiled on sandwich panel construction in an experimental house unit at the Forest Products Laboratory.

Machines suitable for the production of chips to meet various specifications of new products utilizing wood chips are described in Report 2160, "Wood-Chipping Equipment and Materials Handling."

"Preservatives for Wood Pallets," Report 2166, points out various preservatives and methods of application that may be used advantageously for lengthening the service life of wood pallets.

Information on an 8-foot tunnel-furnace test used to investigate surface flammability for building materials has been incorporated along with other pertinent data in a recently revised publication entitled, "Fire-Test Methods Used in Research at the F.P.L.," Report 1443.

Editors Note

The September issue of the JOURNAL carried an article "Bacterial Attack on Pine Logs in Pond Storage," by E. L. Ellwood and B. A. Ecklund. Because of space limitations, the acknowledgment section of the article was deleted by the editor. At the request of the authors, the acknowledgments are reprinted below.

Acknowledgments

Many people and organizations either were consulted or participated in phases of this investigation. Particular acknowledgment is due William McCudden and Carl Tucker of the Diamond Gardner Corporation, who initiated the study with the California Forest Products Laboratory and facilitated many phases of the investigation. Acknowledgment of consultations is made to Clark Heritage, consultant to Diamond Gardner Corporation; A. W. Stout, Western Pine Association; Elizabeth McCoy, University of Wisconsin Department of Bacteriology, and Peter Ark, University of California Department of Plant Pathology. At the University of California Forest Products Laboratory, Shirley McTernan assisted with the bacteriological phases of the investigation, and David L. Brink with chemical aspects of water treatment.

NAMES in the NEWS

Col. J. H. Jenkins, Chief, Forest Products Laboratories of Canada, is presented with a copy of the new Timber Construction Manual of the Canadian Institute of Timber Construction by R. F. DeGrace, P. Eng., Executive Vice-President of the Institute. The 368-page engineering manual is the result of more than four years' work on standard specifications in which both FPL of C staff and Institute personnel participated. The presentation was made at the Ottawa Laboratory. Bound in green flexible binding, 6" x 9" size, opens flat for drawing board use. Available on approval from Canadian Institute of Timber Construction, P. O. Box 57, Toronto 9, Ontario; $6.50.

Dr. Ellis B. Cowling of the U. S. Forest Products Laboratory has been awarded a Public Health Service Fellowship to pursue research on the enzymology of wood deterioration during the 12 months beginning in September, 1959. This research is being conducted in cooperation

with Dr. Birgitta Norkrans of the Royal Pharmaceutical Institute in Stockholm, Sweden, and Dr. Nils Purot of the Biochemical Institute of the University of Uppsala, Uppsala, Sweden. The work is an extension of Dr. Cowling's dissertation on the comparative biochemistry of the decay of wood by white- and brown-rot fungi.

Thoughtful expressions are worn by William G. Van Beckum (left), Director of Research and Development for The Pacific Lumber Company, and Nicholas V. Poletika, Director of Research and Development for Union Lumber Company, at recent Redwood Industry Conference at Santa Rosa, Calif. The conference, attended by some 200 top redwood industry leaders, was sponsored by the California Redwood Association to acquaint industry representatives with the challenge being made to redwood markets by highly competitive metals, plastics and other wood substitutes.

Robert A. Hann, forest products technologist at the Forest Products Laboratory, Madison, has been granted a fellowship for the 1959–60 academic year by North Carolina State College at Raleigh. Hann intends to concentrate on courses in wood chemistry conducted by Dr. Alfred J. Stamm, who recently retired from the Lab after 34 years. Hann has been doing research work in the development of particle board, a product made by binding wood chips together under high pressure.

EMPLOYMENT *Opportunities*

Inquiries concerning employment listings or ads to be placed in the JOURNAL should be addressed to FPRS Employment Service, P. O. Box 2010, University Station, Madison 5, Wis. Correspondence is kept confidential.

Positions Offered

E–368—Laboratory assistant and plants inspector wanted. Must have BS in wood technology. No experience required. Should be 25 or younger. (Nov.)

E–370—Trade association expanding field promotion department. Will add 19 men at locations throughout U. S. Must have qualifications and understanding equivalent to that of graduate or new graduate in architecture, civil engineering, industrial design agricultural engineering, or forest products. Requires ability for self expression and capacity for aggressive promotion. (Nov.)

E–369—Developing engineer for expanding technical group on West Coast. Company manufactures lumber, veneer, allied products. Will be responsible for design of pilot plants for new products and engineering in existing plants, some product development. Must be able to work with production personnel. Engineering degree, experience in forest products, ability to work with little supervision required. Salary attractive. (Nov.)

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PROGRESS IN CHARCOAL PRODUCTION

Continuous Residue Carbonization[1]

E. E. DARGAN
Conway Charcoal Industries, Inc.,
Conway, South Carolina

W. R. SMITH
Southeastern Forest Experiment Station,
Forest Service, Asheville,
North Carolina

Sawdust is conveyed by screw feeds through tubes in a chamber maintained at 800°–900° F. Sawdust is carbonized in 2 hours, then sprayed with steam. No supplemental heat is needed after the carbonization is started.

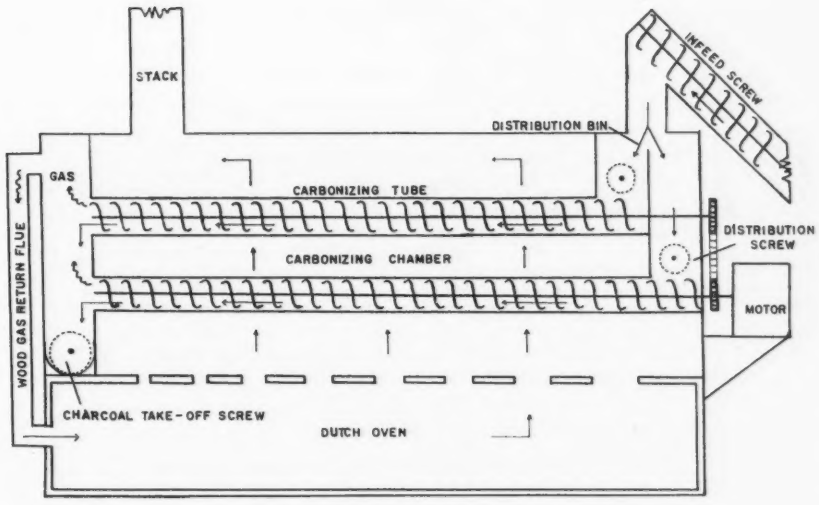

Fig. 5.—Flow chart, fine wood residue carbonizer.

THE PRODUCTION OF CHARCOAL is one of the oldest industries in the world. For centuries, the accepted practice was to burn wood in a pit or on top of the ground, and smother the fire with enough dirt or other materials so that it carbonized without burning to ash. This ancient method is still used, even in America, because it requires little or no capital investment and can be a simple farm operation. The disadvantages are the unpredictable yield (usually low), the amount of labor required, and the dirt inevitably mixed with the charcoal.

The Authors: Ervin E. Dargan is president of Conway Charcoal Industries, Inc. Walton R. Smith is chief of the Division of Forest Utilization Research at the Southeastern Station.

In modern times, there have been many developments in charcoal manufacture to assure standardization of yield and quality, to recover by-products, and to increase production to meet increasing demands. Many successful units have been developed, from round beehive metal kilns, small square metal kilns, masonry and cement block kilns that hold from 1 to 100 cords, to closed retorts with recovery systems. The raw material used in most of these modern charcoal kilns has been round wood or chunk wood.

Scientists and wood industrials have dreamed of developing a practical method to convert bark, chips, sawdust, and shavings into charcoal at a profit. Much research has been done on this problem, and the patent offices are full of ideas, many untried.

Stamm[2] developed a process for converting sawdust to charcoal by passing it through molten metal. Fundamental studies involving the principles associated with this method of fine carbonization have been conducted at the U. S. Forest Products Laboratory.

There has been research by Morgan[3] and associates at Georgia Tech on producing charcoal from sawdust by the fluidized-bed process. Although this method has interesting possibilities, it has not been tried commercially.

While many scientists were busily engaged in varying types of research, an inventive Danish–Canadian named

[1] Presented at Session XVIII, General, FPRS 13th National Meeting, June 28–July 3, 1959, San Francisco.

[2] Stamm, A. J. 1949. Destructive distillation of solids in a liquid bath. U. S. Patent, No. 2,459,550.

[3] Morgan, L. W., Armstrong, G. M., Jr., and Lewis, H. C. Distillation of hardwood in a fluidized bed. Chem. Engin. Prog., Vol. 49, No. 2, 4 pp. illus. 1953.

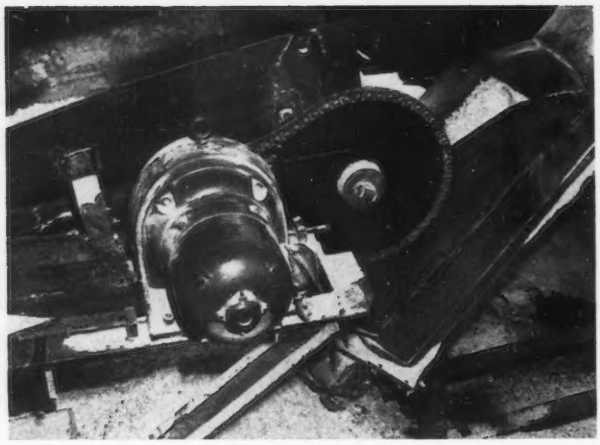

Fig. 1.—Wood residue is conveyed from a storage bin to an inclined tube with a screw feed.

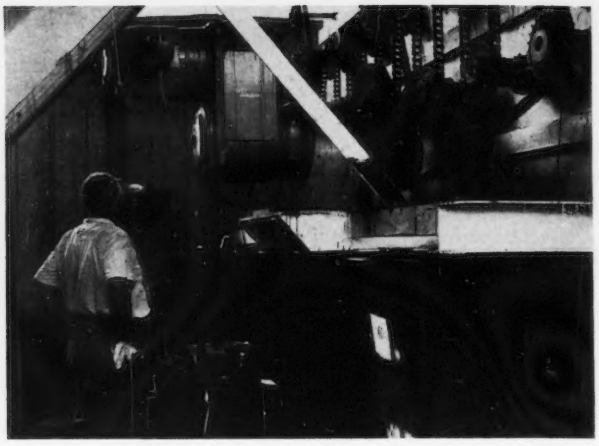

Fig. 2.—A variable speed motor drives the spiral screws in the thirteen carbonizing tubes.

Svend Thomsen was tackling the problem on his own from a purely practical approach in Ontario, Canada. Educated in Denmark and at Rensselaer in New York, he developed exceptional abilities as a topnotch machinst with imaginative ideas. In his private, poorly equipped laboratory, he first established the required carbonizing temperatures and other fundamental information for manufacturing charcoal. He then set about to make a continuous carbonizing unit. Essentially, the unit employs a number of tubes with screw-feeds that slowly convey the sawdust through the tubes. The tubes themselves pass through a heating chamber, where the temperature is maintained at 800° to 900°F. It requires from one to two hours for the sawdust to pass through this area, during which time it is fully carbonized. The carbonized sawdust then passes to a single exit tube, where it is sprayed with steam for the purposes of partially activating the charcoal and reducing the temperature.

A feature of the carbonizer is that it operates without supplemental heat, once the process is under way. A portion of the gases from the carbonization process are vented into the combustion chamber, where they are burned to provide sufficient heat to carry on the operation.

Air is excluded from the carbonizing tubes by means of the wood residue forming its own air seal in the entering conveyor tube. The charcoal seals the air from the exit tube. Also, some pressure develops inside the tubes during carbonization.

An arrangement was made whereby Mr. Thomsen moved his entire operation to Conway, South Carolina, where the Charcoal Industries, Inc., was formed with the purpose of developing a commercial unit for converting wood residue into charcoal briquets and other charcoal products. The company also plans to make this equipment available to the wood-using industries.

The first job was to develop a carbonizing unit that would produce approximately 10 tons of charcoal in 24 hours. (Mr. Thomsen's original model in Canada had a rated production of only 3 tons in 24 hours.) The second job was to develop inexpensive briquetting equipment that would handle the production capacity of the carbonizer.

The first objective has been completed and the carbonizer is operating and ready for the wood-using industry. Charcoal Industries is in the middle of developmental work on the briquetting machine and will report on it when it is ready for commercial use. This paper will be concerned primarily with the carbonizing unit.

The carbonizing unit is constructed of brick and concrete, 31.4 feet long, 15 feet wide, and 12 feet high. A single metal tube with a screw conveyor carries the wood residue to the entrance hopper (Fig. 1), where it is distributed evenly to 13 parallel tubes that carry the material through the combustion chamber (Fig. 2). These tubes drop the carbonized residue into a single exit tube that carries the charcoal to storage vats or directly to a briquetting machine (Fig. 3). The main structure has a dutch oven underneath. The heat passes through ducts in the top of the dutch oven to the upper heating chamber, where the tubes are located. A wood fire is started in the dutch oven for several hours to get the temperature up to 800°F., before the carbonizing process is started. After the carbonizing process is under way, the products of carbonization (wood gases and so on) are diverted from the carbonizing tubes to the dutch oven, and the process then becomes automatic without supplemental heat (Fig. 4). A flow chart of the process is shown in Fig. 5.

Sawdust, bark, shavings, hardwood chips, and pecan shells have been successfully carbonized. The material carbonized varied from about 5 percent moisture content to approximately 150 percent moisture content, but the latter takes longer to remove the excessive amount of moisture.

The Southeastern Forest Experiment Station of the U. S. Forest Service has served as advisor and consultant in the developmental work, and has conducted studies of moisture content of residue, production rates, and quality of the charcoal. From these studies made during the shakedown runs, a great deal has been learned, and equipment design has been improved.

The first studies were made in March, 1959. Moisture contents of mixed pine shavings and sawdust averaged 141.6 percent; fresh pine sawdust 81.6 percent; and hardwood chips 79.2 percent. The rate of charcoal production during this test was 47 pounds per hour or 5.7 tons per 24 hours. Insufficient data were obtained to determine the yield of charcoal from a ton of wood residue, because it is impossible to correlate the charcoal production with infeed except over a long period of time. The charcoal obtained

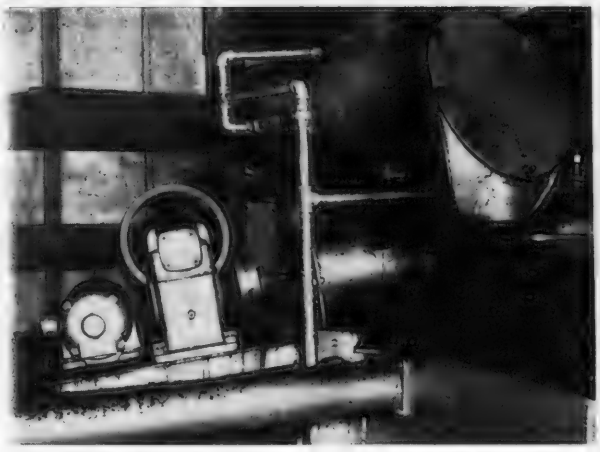

Fig. 4.—Back end of carbonizer, showing bypass of gases to dutch oven, drive for exit of charcoal through tube leaving carbonizer at right, and experimental fractionating device for collecting wood distillates.

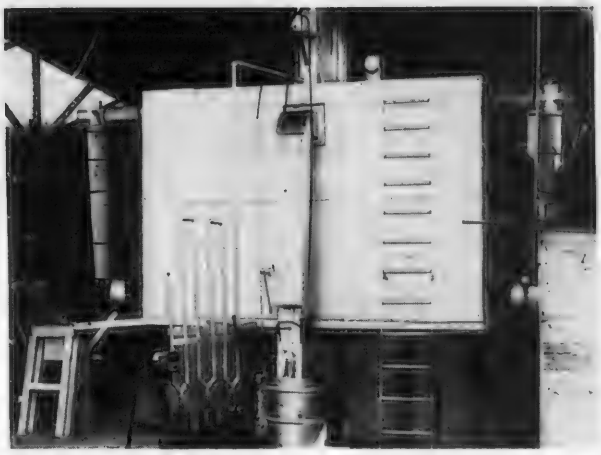

Fig. 3.—An exit tube (upper) conveys the carbonized residue to a mixing vat prior to briquetting (lower) or to a conveyor tube to a storage bin (center). Steam is sprayed into charcoal for cooling and activating.

from this test was analyzed at the Forest Products Laboratory, with the following results on a basis of oven-dry weights:

Average moisture content of charcoal	1.79 percent
Volatiles	27.17 percent
Ash	4.62 percent
Fixed carbon	68.21 percent

This run had a higher volatile content and lower fixed carbon content than is generally desired for high-grade commercial charcoal, but again the extremely high moisture content of wood residue being tested should be noted.

Further research tests were made in early June with pine planer shavings. Data were taken for the infeed of shavings and outfeed of charcoal for 2 one-hour periods on two separate days while the unit was operating continuously. Moisture content of the shavings ranged from 11 to 47 percent from random samples and averaged 27.4 percent. Insufficient data were obtained for the indication of precise yields from this light-weight material, but the percentage yield was over 20 percent on an oven-dry basis.

An analysis of this charcoal at the Forest Products Laboratory gave the results shown in Table 1 on an oven-dry weight basis.

In a subsequent run on dry oak shavings, the charcoal yield over an 8-hour period amounted to 30 percent, and the production capactiy of the equipment was 5-½ tons per 24 hours.

Another production test was made on hardwood chips and planer shavings. The results were encouraging because the percentage yield increased and charcoal quality was higher. The results of these tests are given in Table 2.

More is being learned each day about the equipment's capacity and its production, which varies greatly with the size and shape of wood residue particles, the moisture content, and the density of the wood residue. With a variable-speed drive, the production rate can be changed to fit the type of residue being carbonized.

The latest production test was made with green gum chips from slabs, fresh from the saw. In a period of 1 hour and 28 minutes, the machine produced 864 pounds of charcoal, which indicates a production of 14,138 pounds in 24 hours or a fraction over 7 tons.

As mentioned earlier, the briquetting machine, which works by hydraulic pressure on the molds to form charcoal briquets from the hot charcoal directly from the carbonizer, has not been perfected. A little more experience is needed on binder types and quantities, on production rates, and the coordination of the briquet machine with the carbonizer before the briquet machine can be put on the market.

In summary, a carbonizing unit has been developed for converting wood residues into charcoal, and this equipment is available to industry. A briquetting machine to use in conjunction with the carbonizing unit is being developed, and it should be available to industry soon.

Table 1.—RESULTS OF CHARCOAL ANALYSIS

Sample No.	Moisture content	Volatiles	Ash	Fixed carbon
1 1	0.88	14.71	1.16	84.13
1 2	.93	20.24	.99	78.77
2 1	.55	13.77	1.17	85.06
2 2	.59	20.23	.98	78.79
3 1	.39	16.33	1.10	82.07
Average	.67	17.16	1.08	81.76

Table 2.—PRODUCTION PER 24 HOURS

	Hardwood chips	Planer shavings
Tons oven-dry material	16.4	14.9
Tons oven-dry charcoal	4.7	4.2
Percent yield (based on oven-dry weights)	28.4	27.9
Av. moisture content, percent:		
Green material	36.2	12.5
Charcoal	1.5	1.8

Kiln Drying Chemically Treated Scarlet Oak and White Oak Lumber[1]

A. E. Lund
School of Forestry, Duke University, Durham, N.C.
M. A. Taras
Southeastern Forest Experiment Station, Asheville, N. C.

Unseasoned lumber was treated with a chemical seasoning agent and dried rapidly with high-temperature schedules. Two methods of treatment were explored: bulk piling with dry salt, and dipping in a solution. Dipping had little effect. The schedules used were too severe for scarlet oak, though dry-spread salt did reduce honeycombing. White oak was dried to a MC of 8% in 10 days with little degrade.

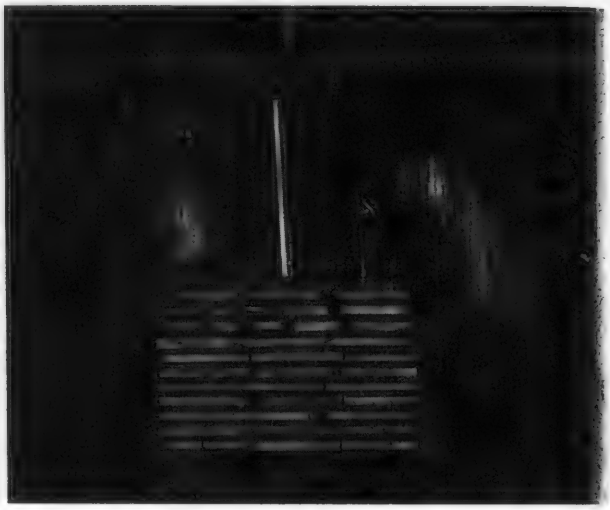

Fig. 1.—Experimental kiln with test charge.

WOOD-USING INDUSTRIES are continually seeking better and faster methods of drying wood with a minimum amount of degrade. Although a large number of woods can be dried in a relatively short time with little or no degrade, there are some commercially important species that require considerable care and time to dry properly. Oaks (*Quercus* sp.) are among the woods used rather extensively throughout the woodworking industries that require considerable care and time to dry.

The purpose of this study was to determine if chemically treated 1-inch oak lumber could be dried satisfactorily with severe kiln-drying schedules.

Chemical Seasoning

In ancient times, wood was soaked in sea water before it was dried to help reduce surface checking, and common salt (sodium chloride) has been used for many years as a layer between boards bulk-piled for air-drying. These processes were not fully understood until after 1930 when the Forest Products Laboratory in Madison, Wisconsin, had completed some preliminary work in chemical seasoning.

The Authors: Anders Lund holds a BSF from Colorado State University, and a MF from Duke. He has worked for the Forest Insect Laboratory and the U.S. Forest Products Laboratory.

Michael Taras received his BS and Master of Forestry degrees from the Pennsylvania State University. He was at the U.S. F.P.L. for over 7 years before he joined the Forest Utilization Research Division at the Southeastern Station.

The following hypotheses were formulated by the Laboratory after its preliminary work:

1. A water-soluble chemical will diffuse into the water contained in green wood, and water in the wood will diffuse into the surrounding chemical solution.
2. The presence of the chemical in unseasoned wood lowers the vapor pressure of the water within the wood, which thus tends to retain more water in the wood and permits the wood affected to remain in a swollen or partially swollen condition while it is being dried in specific relative humidities.[3]

To use chemical seasoning agents effectively it is necessary to understand the basic concepts and ideas that govern their application and use. In the normal seasoning process, moisture in wood moves from a region of higher moisture concentration to a region of lower concentration. For wood to dry under normal conditions, therefore, it is necessary that the surface of the lumber be drier than the interior. This establishes a moisture gradient that permits the more moist regions in the interior to dry by the movement of moisture towards the surface. The steeper the gradient, the faster the drying rate.

When the moisture content of wood falls below 30 percent, or the fiber saturation point, the vapor pressure of the moisture becomes less; and when the wood is completely dry, the vapor pressure is zero. In normal drying, where the core is wet and the outer layers are below fiber saturation point, unequal moisture distribution causes differential shrinkage in the wood and produces stresses that result in surface and end checks.

In chemical seasoning, when the chemical is ideally applied, it enters approximately the outer one-tenth of the thickness of the wood and reduces the vapor pressure of the water in this zone. The water in the interior of the wood retains its high normal vapor pressure. The amount of vapor-pressure reduction in the outer zone can be controlled by the type and quantity of chemical agents used.

Thus, at any given temperature and relative humidity, the water in the core of the wood has a higher vapor pressure than the solution in the shell or outer fibers of the wood. Therefore, the water in the core will move along the vapor-pressure gradient from the core toward the outer fibers.

If kiln conditions are set so that the relative vapor pressure of the atmosphere is lower than the relative vapor pressure of the chemical solution, the wood begins to dry. At the

[1] Presented at the Fall Meeting of the Carolinas-Chesapeake Section, FPRS, Oct. 31—Nov. 1, 1958, in Roanoke, Va.

[2] A cooperative aid project between the School of Forestry, Duke University, and the U.S. Forest Service, Southeastern Forest Experiment Station.

[3] Anon. 1948. Experiments in the chemical seasoning of wood. U.S. Forest Prod. Lab. Rpt. R1701.

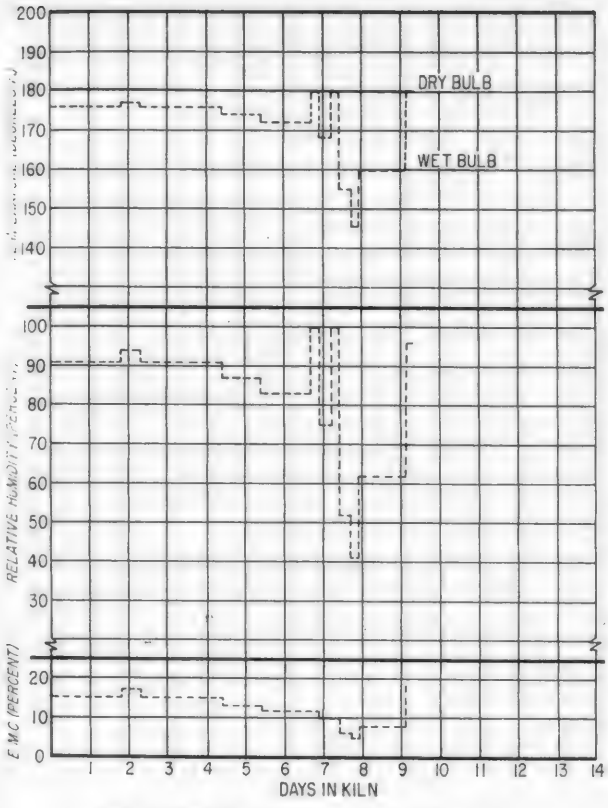

Fig. 2.—Drying schedule used in kiln run 1.

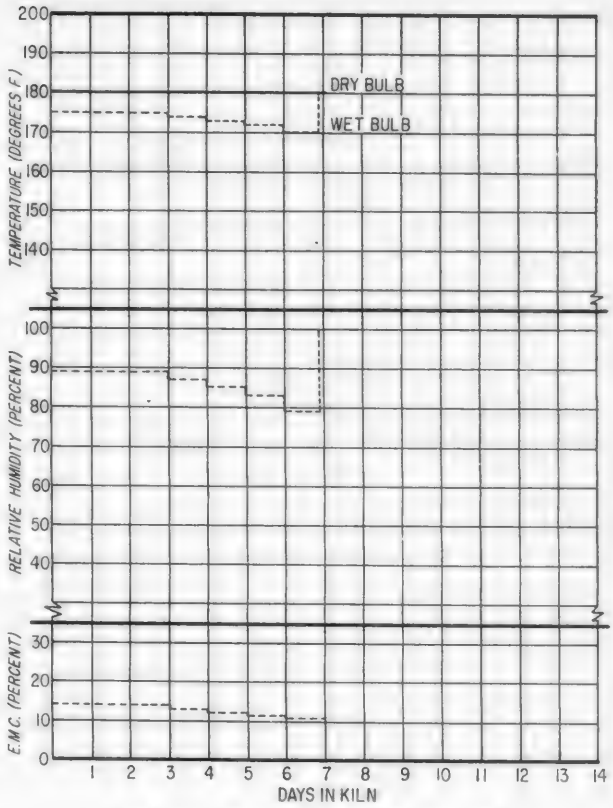

Fig. 3.—Drying schedule used in kiln run 2.

same time, because of the vapor-pressure gradient within the wood, moisture is moving from the center of the wood to the surface where it is being evaporated.

If the vapor pressure of the air controlled by the temperature and relative humidity is equal to or greater than the vapor pressure of the chemical solution, the surface fibers of the wood will remain moist, and no drying will take place. Research on chemical seasoning at the U. S. Forest Products Laboratory has shown that condensation results if the relative vapor pressure of the atmosphere exceeds the vapor pressure of the chemical solution in the outer layers of the wood.

If such condensation is permitted for any length of time the condensing water tends to leach out the chemical and cause corrosion problems in the kiln.

Experimental Procedure

Four kiln runs were made in this study on two species of oak: scarlet oak (*Quercus coccinea* Muenchh), and white oak (*Quercus alba* L.). The first two kiln runs were preliminary in scope and were used to establish the temperature schedules for runs 3 and 4.

The chemical substance used was Morton Lumber Cure, a buffered salt, consisting essentially of sodium chloride and some undisclosed corrosion-inhibiting additives.

The lumber was sawn from six trees, three scarlet oaks and three white oaks, selected on the basis of similarity of age, vigor, form, height, and size. Only the 16-foot butt of each tree was sawn into lumber. To minimize air-drying of the lumber, the logs were sawn just prior to the time each kiln run was made. The logs were sawn by methods used to obtain the best quality possible, except that no boards were cut less than 6 inches wide. Position of each 16-foot board within each log was noted, and each 16-foot board was cut into two 8-foot lengths to accommodate the size of the experimental kiln. In kiln runs 3 and 4, one-half of the 8-foot boards were treated chemically and the other half were used as controls and dried in the same charge.

Two methods of chemical treatment were studied. The first treatment consisted of bulk-piling the green 8-foot boards with alternating layers of the dry salt; 140 pounds of salt were applied per thousand board feet of lumber. The bulk piles were covered with a waterproof plastic and allowed to stand for 5 to 7 days, after which they were assembled into a kiln charge. This treatment was applied to the lumber dried in kiln runs 1, 2, and 3.

The second type of chemical treatment was applied to the lumber dried in kiln run 4. The lumber was dipped in a 25 percent solution of the chemical for 20 seconds and then allowed to drain until drip free (about 30 seconds). The solution contained by weight 25 percent of the buffered salt, 4 percent starch, and 71 percent water, as recommended by the manufacturer.

Drying was done in an experimental cross-circulation kiln. Fig. 1 shows the experimental kiln with a test charge ready for drying. The boards used in the respective kiln runs were selected randomly from each log and then randomly placed in the kiln charge. In kiln charges 3 and 4, where both scarlet oak and white oak were dried together, the species were kept separate and not randomly mixed. The boards in each course of lumber were placed edge to edge and stickered with five stickers to minimize warping. The drying schedules (figs. 2, 3, 4, 5) called for considerably higher temperatures and relative humidities than those ordinarily used in chemical seasoning. Relative humidities above 75 percent should prevent drying, but substantial drying occurred from the start in each run. Severe corrosion of the kiln indicated that some leaching of the chemical occurred, which possibly affected the vapor pressure in the surface zone.

Conventional procedures[4,5] were used for determining moisture content and preparing kiln samples. In kiln runs 1 and 2, eight kiln samples were used in each charge. In runs 3 and 4, twenty-four kiln samples were used per

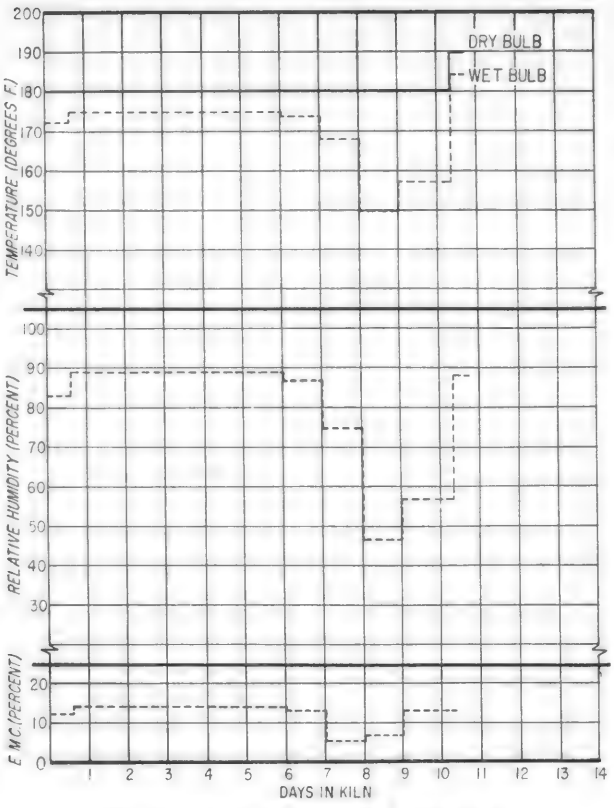

Fig. 4.—Drying schedule used in kiln run 3.

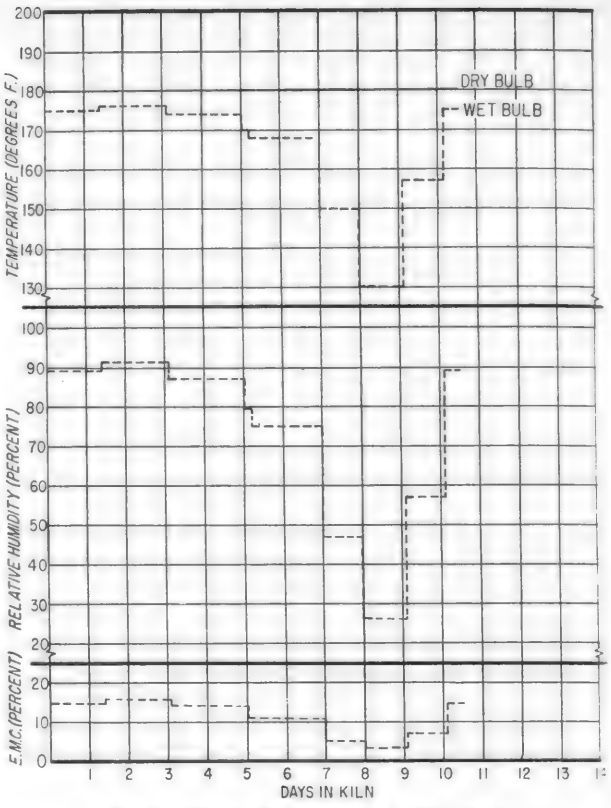

Fig. 5.—Drying schedule used in kiln run 4.

charge. In addition to the 24 samples used in charges 3 and 4, several extra samples were placed in the charge so that periodic casehardening, miosture content, and moisture gradients tests could be made as drying progressed, without destroying the kiln samples used to measure the drying rate of the charge. All kiln samples were weighed and the above tests were made on the extra samples every 24 hours.

All the lumber used as test material was graded on the poorest face before it was kiln dried, in accordance with the National Hardwood Manufacturers Rules of January 1955. Defects on the poorest face were delineated and the amount of clear and defective area determined. After all the boards were dried, they were regraded and the clear and defective areas recalculated. The amount of sweep, cup, bow, and twist was also measured, and specific gravity was calculated on an ovendry basis. After these determinations, the boards were surfaced to a thickness of ¾ inch. This surfacing removed sufficient material to expose any honeycomb checks in the interior. The length of all exposed honeycomb checks was measured on the face that showed the greatest number and longest checks. The extent of honeycombing was expressed in linear inches per surface board-foot.[6] Because unseasoned oak is prone to severe honeycombing when dried at high temperatures, the extent of honeycombing was used as a primary criterion for measuring the effectiveness of the chemical treatment on lumber quality under severe kiln drying conditions.

Discussion of Results

In commercial drying, it has been generally observed that white oaks are more difficult to dry than red oaks. Two exploratory studies in chemical seasoning[7,8] indicated, however, that certain red oaks are more difficult to dry than white oaks, contrary to general opinion. The first two kiln runs (1 and 2) of this study were preliminary in nature, and established the maximum temperatures and humidities at which scarlet oak and white oak lumber could be dried without serious degrade. Kiln run 1 was made on scarlet oak alone because of the indications of the previous works. A severe, noncyclic kiln schedule was devised, based on a dry-bulb temperature of 180°F. and a wet-bulb temperature of 176°F. as the initial conditions. This gave a relative humidity of 91 percent and an equilibrium moisture content of 15.5 percent. Kiln conditions were adjusted throughout the run to maintain the maximum drying rate and at the same time keep degrade to a minimum. Every 24 hours, the boards in the charge were examined for end checks and surface checks. Surface check examination was restricted to the top layer of boards. Whenever the lumber in the charge showed evidence of checking the drying conditions in the kiln were made milder. Fig. 2 shows the entire schedule for kiln run 1 with the adjustments made at periodic intervals. Changes in the schedules toward milder conditions indicate the occurrence of checking at that time.

Fig. 3 is the schedule used in kiln run 2 in which only the white oak was dried. The initial conditions of this run were slightly more severe than those used in kiln run 1. The initial drying conditions were 180°F. dry bulb and 175°F. wet bulb, which gave a relative humidity of 89 percent and an equilibrium moisture content of 14 percent. Though the drying conditions in this run were more severe than those in kiln run 1, it was not necessary to make conditions milder, as was the case in run 1, which indicates that the treated white oak could withstand

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Table 1. SUMMARY OF TREATMENTS FOR KILN RUNS 1, 2, 3, AND 4

Kiln run	Species	Lumber: Specific gravity	Lumber: Bd. ft. in charge	Lumber: Boards No.	Lumber: Treated boards No.	Lumber: Control boards No.	Lumber: Kiln samples No.	Moisture content: Green %	Moisture content: Dry %	Chemical Treatment: Treating method	Chemical Treatment: Treating time Days	Chemical Treatment: Amt. of chemical applied lb/MBF	Chemical Treatment: Amt. of chemical retained lb/MBF	Chemical Treatment: Approximate penetration Inch	Initial drying conditions: Dry bulb F°	Initial drying conditions: Wet bulb F°	Initial drying conditions: Relative humidity %	Initial drying conditions: EMC %	Drying time: Drying period da's/hrs	Drying time: Equalization da's/hrs	Drying time: Conditioning da's hrs	Drying time: Total da's/hrs
1	Scarlet oak	0.65	150	23	23	0	8	80	15	Bulk piled	5	140	100	3/32	180	176	91	15.5	9-3	0-0	0-5	9-8
2	White oak	.70	160	23	23	0	8	50	14	Bulk piled	8	140	110	1/8	180	175	89	14.0	6-22	0-0	0-2	7-0
3	Scarlet oak	.67	410[1]	32	16	16	12	94	10	Bulk piled	5	140	105	3/32	180	172	83	12.0	8-21	1-11½	0-5	10-13½
	White oak	.69	- - -	32	16	16	12	74	8.5													
4	Scarlet oak	.68	444[1]	32	16	16	12	97	8	20 sec. dip	- -	25%[2] solution	10	1/64	180	175	89	14.0	9-1	1-4	0-7½	10-12½
	White oak	.68	- - -	32	16	16	12	79	8.5													

[1]Includes white oak and scarlet oak.
[2]Chemical was applied by dipping lumber for 20 seconds in a 25% solution of Morton's Lumber Cure.

Table 2.—SUMMARY OF RESULTS FOR KILN RUNS 1, 2, 3, AND 4

Kiln run	Species	Treatment	Boards dropping in grade	Defective area increase	Honeycombing	Warping: Cup	Warping: Sweep	Warping: Twist	Warping: Bow
			Percent	Percent	Lin. in./bd. ft.	Inch	Inch	Inch	Inch
1	Scarlet oak	Bulk piled	8.7	0.6	3.46	0.073	0.160	0.228	0.054
2	White oak	Bulk piled	0.0	.3	0.16	.075	.099	.068	.049
3	Scarlet oak	Bulk piled	12.50	.4	1.16	.06	.16	.06	.03
		Control	18.75	.09	17.12	.08	.25	.17	.06
	White oak	Bulk piled	18.75	.2	1.17	.05	.14	.20	.06
		Control	31.25	.5	5.27	.06	.31	.45	.12
4	Scarlet oak	Dipped	81.25	2.6	23.28	.10	.41	.08	.24
		Control	93.8	9.0	40.63	.07	.22	.08	.24
	White oak	Dipped	25.0	.5	1.61	.05	.16	.11	.16
		Control	0.0	.7	3.73	.01	.08	.09	.13

higher temperatures during drying than could the scarlet oak.

A summary of the treatments for kiln runs 1 and 2 are shown in Table 1, and the results of the treatments are shown in Table 2. These data show that only a negligible amount of warping occurred, and the increase in defective area was very small. About 9 per cent of the scarlet oak boards dropped in grade, while none of the white oak boards were down-graded after drying. Honeycombing was considerably greater in the scarlet oak run (3.73 linear inches per surface board-foot) than in the white oak, which showed 0.16 linear inch of honeycombing per surface board-foot. This difference in the degree of honeycombing may be attributed to the following reasons:

1. White oak is less prone to honeycombing, as indicated by previous work.
2. The scarlet oak picked up less of the chemical than the white oak and the depth of penetration was less, perhaps because the sacrlet oak was bulk piled only 5 days, whereas the white oak was bulk piled for 8 days.
3. The sechdule used may have been to severe for scarlet oak.

In view of the results obtained in the preliminary runs, kiln runs 3 and 4 were made according to the schedules shown in Figs. 4 and 5, respectively. In both runs an equal number of treated and control boards of each species were dried together.

The treated material used for run 3 had been bulk piled for 5 days with alternating layers of salt, spread at a rate of 140 pounds per thousand board-feet. The initial drying conditions were 180°F. dry bulb, 172°F. wet bulb, 83 percent relative humidity, and an equilibrium moisture content of 12 percent. These initial conditions were slightly more severe than those used in runs 1 and 2, and proved too severe. It was necessary to make the drying conditions milder after ½ day of drying, and conditions were changed to 180°F. dry bulb, 175°F. wet bulb, 89 percent relative humidity, and 14 percent equilibrium moisture content. These conditions were maintained for 5-½ days, after which the drying schedule was made progressively more severe as the moisture content of the stock decreased.

The treated material used in kiln run 4 was dipped in a 25 percent solution of the chemical seasoning agent. The initial drying conditions for this run were the same as those used in run 2: 180°F. dry bulb, 175°F. wet bulb, 89 percent relative humidity, and 14 percent equilibrium moisture content. Although these conditions were slightly less severe than those used initially in run 3, it was necessary to make the schedule milder after 1-½ days of drying because of the checking that began to appear. The conditions were changed to 180°F. dry bulb, 176°F. wet bulb, 91 percent relative humidity, and 16 percent equilibrium moisture content. These conditions were maintained for 1-½ days and then changed to progressively more severe conditions until the charge was dried to 8.5 per cent moisture content. A summary of the treatments applied to the materials in runs 3 and 4 is shown in Table 1.

Every 24 hours during the drying period, kiln samples were weighed and the moisture content of the charge was determined. The rate of moisture loss, based on the moisture content of the kiln samples, is shown in Fig. 6 for kiln 3 and Fig. 9 for kiln run 4. These curves illustrate the influence of chemical treatment on the drying rate of the respective species.

In kiln run 3, the influence of chemical treatment on rate of moisture loss in scarlet oak is quite apparent by the spread in moisture content between treated and untreated material. The spread first began to appear about 12 hours after drying was started. From this point on the treated material maintained a higher moisture content than the controls, and the spread in mois-

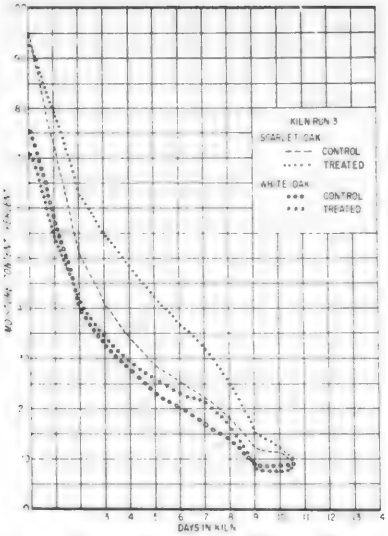

Fig. 6.—Drying rate for treated and untreated scarlet and white oak in kiln run 3.

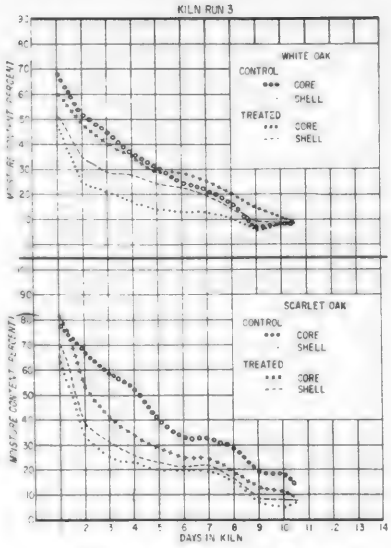

Fig. 7.—Moisture gradient between shell and core of treated and untreated scarlet and white oak in kiln run 3.

ture content between treated and untreated material became progressively greater. It reached a maximum spread after 3 days of drying (13 percent spread in moisture content). This spread was maintained until the fifth day of drying, after which the spread began to decrease. At the end of the drying period (8 days, 21 hours), the spread in moisture content between the treated material and controls was approximately 3 percent. The charge was then equalized to 10 percent moisture content and conditioned for 5 hours to relieve stresses.

The white oak that was given the same chemical treatment and dried in the same charge was not affected by the chemical treatment for the first few days of drying as was the scarlet oak. The curves representing white oak in Fig. 6 show that the treated material and controls dried at about the same rate for the first 4 days. After this period, a small spread in moisture content appeared between treated material and the controls. The maximum spread in moisture content (4 percent) between treated material and controls appeared after 7 days of drying, and as in the scarlet oak, the moisture loss was slower in the treated material than in the controls.

In addition to the moisture content data obtained from the kiln samples every 24 hours, moisture content of the shell and core of treated and untreated material was determined from specimens cut from the extra kiln samples. The results obtained from these data (Fig. 7) represent the moisture gradient that existed in the lumber during drying. In the drying of lumber, a steep moisture gradient between shell and core indicates the development of high stress in the lumber which may induce seasoning defects. The objective in chemical seasoning is to reduce this gradient in order to minimize the internal stresses that develop. Fig. 7 shows the influence of chemical treatment on the reduction of the moisture gradient in scarlet oak and white oak lumber dried in run 3. In white oak (upper part of Fig. 7) the spread in moisture content between the shell and core of the untreated material is about twice as large as the spread in moisture content in the treated material. The treated material reached a maximum spread of only 12 percent after 2 days of drying, whereas the controls had a maximum spread of 27 percent. The sacrlet oak data (lower part of Fig. 7) displays the same form as the data for white oak. The maximum spread in moisture content between shell and core of the untreated material was 35 percent; treated material had a maximum spread of 13 percent.

The apparent influence of chemical treatment on the rate of moisture loss and moisture gradient within the lumber (Fig. 6 and 7) is further substantiated by the large difference in the degree of honeycoming in the treated and untreated material. The extent of the honeycombing is shown in Table 2. Treated scarlet oak had an average of 1.16 inches of honeycomb per linear board-foot, as compared to 17.12 inches for the untreated. White oak, treated and dried under the same conditions, had an average of 1.17 inches of honeycomb per linear board-foot for the treaded stock compared to 5.27 inches for the untreated stock. The large difference in the degree of honeycombing between the scarlet oak and white oak controls corroborates previous information that white oak is less prone to honeycombing when dried at high temperature than are some red oaks. Chemical treatment proved quite helpful in reducing the amount of honeycombing in both species. Fig. 8 shows the cross sections of several boards dried in run 3.

Kiln run 4 was made on scarlet and white oak boards that were treated by dipping the stock in a 25 percent solution of the chemical. This treatment had little or no effect on the rate of moisture loss between treated and untreated material (Fig. 9). The curve shows that the rate of drying was approximately the same for treated and untreated material of both species. The moisture gradient bewteen shell and core was influenced only slightly (Fig. 10). The treated white oak in kiln run 4 (Fig. 10) shows a maximum spread in moisture content between shell and core of 29. percent after 1 day of drying, compared to a maximum spread of 13 percent for the treated white oak in kiln run 3. The magnitude of the spread in moisture content between shell and core for scarlet oak in run 4 is still larger than for the white oak; it reached a maximum of 33 percent.

These differences in the effect of chemical treatment on drying rates and moisture gradients between kiln runs 3 and 4 are attributed to the differences in concentration of the chemical contained in the wood. Run 3 had a retention of 105 pounds of chemical per thousand board-feet, while the lumber in run 4 had a retention of only 10 pounds of chemical per thousand board-feet. Honeycombing (Table 2) was rather severe in the scarlet oak controls and treated material, an average of 40.63 and 23.28 linear inches of honeycomb per board-foot respectively. Conversely, white oak, which is less prone to honeycombing, showed only a slight increase over the amount in run 3 when absolute values are compared; however, on a percentage basis, this small gain (0.44 inch) represents a 39 percent increase.

Fig. 11 shows cross sections of certain boards dried in run 4. Regardless of the manner in which these differences between runs 3 and 4 are analyzed, the data all indicate that, for this chemical treatment to be effective high concentrations are needed with the high temperature schedules used in this study. The optimum retention of chemical cannot be determined from this study, and it may be possible that lower concentrations than those used in runs 1, 2, and 3 might be quite effective in reducing honeycombing.

This study has definitely demonstrated that the use of a chemical in kiln drying at high temperatures and relative humidities is effective in reducing the amount of honeycombing (percentagewise) in green oak. How

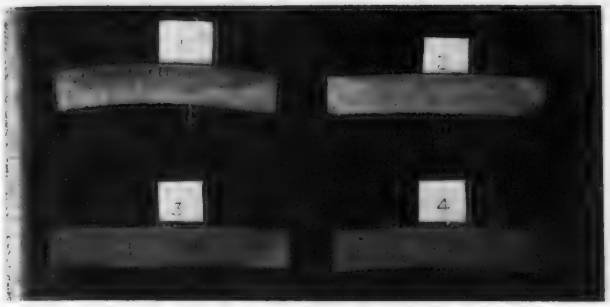

Fig. 8.—Cross sections of treated and untreated scarlet and white oak boards showing internal condition of boards after drying (kiln run 3).
(1) Untreated scarlet oak (3) Untreated white oak
(2) Treated scarlet oak (4) Treated white oak

Fig. 11.—Cross sections of treated and untreated scarlet and white oak boards showing internal condition of boards after drying (kiln run 4).
(1) Untreated scarlet oak (3) Untreated white oak
(2) Treated scarlet oak (4) Treated white oak

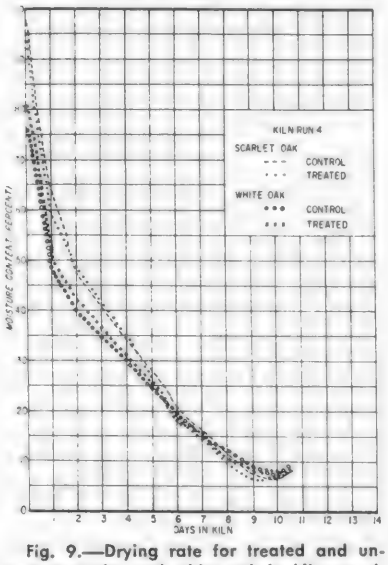

Fig. 9.—Drying rate for treated and untreated scarlet and white oak in kiln run 4.

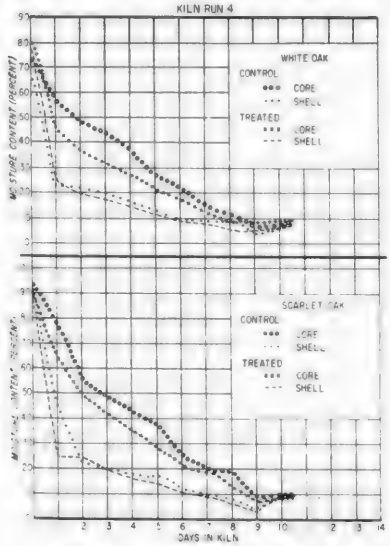

Fig. 10—Moisture sections of gradient between shell and core of treated and untreated scarlet and white oak in kiln run 4.

ever, these conditions cannot be used in present commercial drying equipment because of corrosion. One should also consider the percentage of boards in which honeycombing did occur, regardless of its magnitude. In run 3, only about 50 percent of the boards were free of honeycombing. In run 4, only 6 percent of the treated scarlet oak and 25 percent of the white oak were entirely free of honeycombing.

Drop in grade is somewhat erratic (Table 2), especially when controls between kiln runs are compared, and it is difficult to explain these variations. In the white oak controls in run 4, where no drop in grade was observed after drying was complete, this discrepancy may be explained by the fact that the majority of the boards used as controls were No. 1 common grade or lower before they were dried. Lumber in these lower grades has considerably more latitude in acceptable defects before they are downgraded.

The percentage increase of defective area (Table 2), as well as the warping, are of relatively low magnitude. It appears from these data that salt treatment did not influence warping or defective area to any great extent.

The corrosion problem resulting from the high temperatures and high relative humidities also requires consideration. The kiln used in these tests corroded badly. Perhaps this could have been prevented by proper coating of the kiln. The costs of frequent inspection and maintenance of a commercial kiln to control corrosion under such conditions are quite likely to be prohibitive. In the drying of salt-treated oak, it is possible that free Cl^- and H^+ ions are present. In combination with warm, moist air, circulating rapidly, these ions would be strongly conducive to corrosion.

Summary of Results

The results of this study are not conclusive, but they indicate that chemical treatment can help to minimize honeycomb degrade when high temperatures and rapid drying schedules are used. The results show:

1. White oak lumber honeycombs considerably less than scarlet oak lumber when dried under the same high temperature conditions, whether treated or not treated with a sodium chloride base chemical.

2. Green, 1-inch white oak can be dried in 8 to 10 days with a limited amount of degrade by using a rapid kiln drying schedule and a chemical seasoning agent, such as Morton Lumber Cure, applied to the lumber dry.

3. Dipping lumber in a 25 percent solution of the chemical used in this study was ineffective in reducing honeycombing under high temperatures.

4. Damage from honeycombing in scarlet oak was reduced considerably when it was bulk piled. Even with this reduction, the drying schedules used in this study were apparently still too severe for scarlet oak. It is believed that a somewhat less severe schedule could be used.

5. While the test methods used in this study show a considerable reduction in the percentage of honeycombing, when comparing treated and untreated specimens, only about 50 percent of the treated boards were free of honeycombing. This, and the corrosion, probably makes the method still unacceptable commercially.

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IMPROVEMENTS THROUGH RESEARCH ON

Thin Circular Saw Blades[1]

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Thin, circular saw blades, though flexible, prone to distort and vibrate, and very sensitive to thermal gradients, are giving 10% more product for the authors. Both theory and practice are presented.

Fig. 11.—Pilot machine for sawing pencil slats.

CIRCULAR SAW BLADES FOR WOOD have been used for two centuries. They are newer than reciprocating frame saws and older than bandsaws. It is not surprising that blades are made thick enough to withstand a multitude of adverse forces. The relative thickness of circular blades causes excessive waste, which frequently limits their use. Table 1 shows the ratios between diameter and thickness of some commercially available blades. The blades become relatively thinner as they become larger, but whether they become relatively stronger or weaker depends on many operating factors.

If thin circular blades and machines to use them are not available to the wood-using industry, it is only because there is no ready answer for those who ask themselves how thinner blades could be made and used. Some say they could make them if only they could be used, while others say they could use them if only they could be made.

The advantage of thinner blades depends on the use to which they are put. For example, the slats for lead pencils (0.20 by 2.63 by 7.25 inches nominal air-dried dimensions) are made from blocks of incense-cedar (*Libocedrus decurrens* Torrey) 2.63 by 2.8 by 7.25 inches. Nine so-called thin circular blades 0.049 by 11 inches are used in a gang to saw 10 slats. There would certainly be an advantage if 11 slats, instead of 10 could be made from the same block, by means of thinner blades. Such blades present great difficulties, however, because they are flexible, prone to distortions or vibrations, and sensitive to thermal gradients.

The operation of circular saws is an art that has been described in publications. When centrifugal forces and tensioning are discussed, they sometimes receive explanations that are pleasantly simple. For example, the stresses in a rotating blade have been likened to those generated by a revolving weight attached to the end of a cord. It is true that such a weight induces centrifugal force, because of its mass and continuously changing direction. This force, although generated at the circumference of rotation, is resisted equally at all points along the string. The mass of a circular blade, however, is not concentrated at the rim, but is distributed. The state of stress induced in the blade depends on the interaction of all the infinitely small particles of mass on each other. Instead of being pleasantly simple, this is complex.

Interesting studies in circular saw blades have been published in about a dozen countries and as many languages. Furthermore, there have been advances in research and technology in related fields such as turbine disks, metal machining, and metallurgy. This paper discusses some problems in the manufacture and use of circular saw blades. Recent pertinent research will be mentioned. Experiments by the authors and their associates will be described; their bearing on the manufacture of pencil slats will be reported. Such studies may have value in other branches of sawmilling and remanufacturing.

Some Problems with Circular Blades

The production of a circular saw blade, from the original steel sheet through the several manufacturing and doctoring operations to the saw arbor, presents several difficulties.

To begin with, the plate stock has directional properties as a result of rolling, and it has residual stresses unless it has been thoroughly annealed afterward. More residual stresses are introduced when the saw blank is made from the plate. Local changes occur in the orientation of the directional properties if the blank is formed by shearing and if the teeth are formed by punching. Such changes near the teeth are reduced, but not eliminated if the teeth are formed by milling. In any case, residual stresses persist unless the blank is fully annealed.

Even if the blank is free from stresses and perfectly flat at this stage of manufacture, the subsequent hardening by heating, quenching, and tempering will almost certainly induce warping unless the blank is securely

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[1] A contributed paper, received March, 1959

clamped. Once a blade is warped, no amount of conventional surface grinding will flatten it.

After the blade is manufactured, the saw doctor must attempt to flatten it, usually by hammering. In so doing, however, he must disrupt the carefully ground surfaces with hammer marks, thus inducing local residual stresses. Additional residual stresses are induced during any subsequent tensioning, which consists of stretching the metal by hammering the blade in concentric annuli. Residual stresses are also introduced by setting and grinding the teeth, or by brazing carbide tips.

Consider now a blade running idle. Any departure from flatness or balance (1)[2] may produce vibration. Even an ideal blade can be made to vibrate by disturbances external to the blade itself. Vibrations arising in the saw machine, or in any other machine close to it, may be transmitted to the blade. A crooked arbor or worn bearings can cause vibrations. Even a very carefully made arbor, unless it is free from axial movement, can vibrate (24), and induce vibration in the rim of the blade.

To prevent external vibrations with which the blade can resonate, it may be necessary to make the machine and its foundation much heavier than would be required by considerations of strength alone. Such a machine, because of its higher mass and resulting higher natural frequency of vibration, would not induce sympathetic vibrations in the blade, and would tend to damp unavoidable vibrations in its own moving parts.

Vibrations have a harmful effect on the running of circular blades. In this connection, Skoglund (20) and Malcolm (14) have both discussed the importance of adequate collars. If the largest possible collar diameter is adopted, the blade will be better supported and therefore stiffer, and less likely to vibrate.

Rotation of any disk induces stresses in it. Centrifugal stresses in a rotating disk are all tensile, according to Stodola (21) and Timoshenko (25), and stiffen it, according to Den Hartog (4). Concurrence with these views is expressed by Barz (3) and Skoglund (20) with respect to circular saw blades. Furthermore, the latter state that such tensile stresses are good. They disagree with some other workers who assert that centrifugal force is bad because it causes the rim to expand disproportionately and to flutter (18, 27). Foyster (6) says that dishing is caused at certain speeds by the centrifugal stress near the center of the blade.

[2] Numbers in parentheses refer to the Literature Cited at the end of this paper.

As early as 1872, Richards (16) reported that: "For a time, and up to a certain point, the rigidity or stiffness of the plate will increase; after this it begins to diminish, until at a very high velocity it becomes as limber and pliant as a piece of paper, and finally will, on its periphery, assume a series of undulations or waves, and is as sensitive to pressure, on the side of the plate, as though it were of paper."

An idling blade receives heat from the arbor. Its central zone becomes warmer than its outer zones, which are continuously cooled by the passage of air. Stresses are thereby induced because the central zone cannot expand freely. Barz (3) calculated these stresses and combined them with the centrifugal stresses. The result indicates that the thermal stresses may be more important than the centrifugal. Lindholm (11) calculated the critical buckling temperature for blades heated in the central zone. Richards (16) had observed this heating of the central zone and of the peripheral zone as well. He wrote: "The least variation in temperature between the eye and the periphery destroys the rigidity of the plate."

Consider next the working blade. Further difficulties arise. The torque that the blade must transmit to the teeth will induce shearing stresses throughout. When the teeth enter the work, the shock induces additional stresses and perhaps vibrations.

The teeth are heated by friction while they cut, and they tend to expand into the gullets. If some of this heat is transmitted to a continuous annulus below the base of the gullets, however, free expansion is restricted by the cooler zones of the blade at lesser radii. Hence, compressive stresses are induced in the heated annulus, and they tend to buckle the blade and make it flutter.

Any deviations of the blade from plane rotation, whatever their cause, may induce lateral rubbing against the wood and therefore zonal heating. Saito and Niga (17) and Skoglund (19) have measured the average radial temperature distribution in a rotating blade heated by friction. Barz (1) has shown that bumps produced on the lateral surface of a blade by previous hammering or other causes tend to expand and become more prominent if the temperature increases. Consequently, if an annular zone containing these bumps gets warmer for any reason, the bumps will be more likely to rub the wood. High temperatures, evidenced by blue spots, will be produced in these local zones and will cause stress concentrations. Permanent deformation often results.

The thermal gradient in a working blade will never be uniform. On the contrary, an unsteady state of temperature, both radially and circumferentially, will exist. Computations of thermal stresses based on simplified assumptions of temperature distribution are very useful, but are insufficient for complete solution of the problem.

It is important to reduce excessive thermal gradients or at least to mitigate their effects. This may be done by several means. Cooling the rim of the blade with water spray is a common practice in sawmills. Heating the middle zone by the friction of packing equalizes the temperature at various radii (6). Tensioning a blade counteracts the compressive thermal stresses near the rim according to Barz (3), Lindholm (11), Sugihara (22), and Skoglund (20). Expansion apertures are made in some blades to relieve the compressive thermal stresses, as well as to cool the rim zone. Barz (3) has shown the benefits of such apertures and has recommended additional studies.

Problems with Thin Circular Blades

The problems of thin circular saw blades are essentially those of circular blades in general, but greatly magnified. A skillful saw doctor can make conventional blades work, but he should not be expected to cope with these magnified problems. Perhaps the most important of these stems from the fact that the lateral stiffness of a plate is directly proportional to the third power of its thickness. Thus, if one plate is made one-half as thick as another, its lateral stiffness is one-eighth. Hence, a thin blade is very flexible and extremely sensitive to any disturbing influence. It follows that such a blade tends to buckle under thermal stresses, as Lindholm (11) has shown. Since excessive tensioning can cause a type of buckling, there results the dilemma of a weaker blade requiring a higher degree of tensioning.

Apart from the difficulty of manufacturing a thin, flat blade, there is the problem of keeping it as flat as may be required, by conventional means. If a blade could be manufactured flat, or straightened without hammering, the hammer marks and the residual stresses usually associated therewith would be avoided, and only the problem of tensioning would remain. Barz (3) has described and illustrated an experimental circular-blade tensioning machine with rolls under adjustable hydraulic pressure. Such a technique would avoid the hammer marks in addition to providing more precise control of the position and magnitude of the pressure applied.

The first question to be considered with regard to tensioning is: What does it accomplish, and how? There

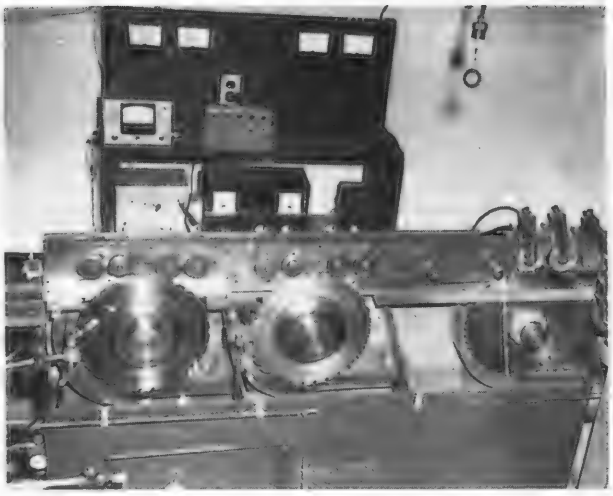

Fig. 1.—Experimental machine for testing blades.

Table 1. CIRCULAR RIPSAW BLADE DIMENSIONS

Type of blade	Diameter (d), in.	Thickness (h), in.	$\frac{h}{d}$
1	2	3	4
Standard, parallel sides	6	0.049	8.2×10^{-3}
	8	0.049	6.1
	12	0.072	6.0
	16	0.083	5.2
	20	0.095	4.8
	24	0.120	5.0
	28	0.134	4.8
	32	0.134	4.2
	36	0.148	4.1
	48	0.165	3.1
	60	0.165	2.7
Standard, tapered one side[a/]	28	0.049	1.7×10^{-3}
	36	0.058	1.6
	36	0.049	1.4
	38	0.049	1.3
Standard for pencil slats, parallel sides	11	0.049	4.5×10^{-3}
	12	0.049	4.1
	16	0.049	3.1
Experimental, tapered	16	0.032	2.0×10^{-3}
	16	0.024	2.5

a/ "Shingle" or "conical" blades.

appears to be considerable agreement that tensioning tends to overcome the adverse effects of heating near the rim. Skoglund (20) and Barz (3) have shown that the so-called tensioning operation induces residual compressive stresses in the zone subjected to the deformation, and residual tensile stresses near the rim. These investigators account for the beneficial results by showing that tensioning helps to counteract the compressive tangential thermal stresses induced near the rim by working friction.

It is widely believed that tensioning stiffens the blade against lateral forces, and permits it to rotate at the desired speed without vibrations. How the tensioning creates these desirable effects has been a subject of considerable speculation but little research. It is a problem worth considering, because if the nature of the stiffening effect could be determined, the means of providing it might be improved.

Some hold that tensioning accomplishes its purpose by counteracting the adverse effects of centrifugal forces. One such hypothesis (12, 18) states that the stretching of the middle zone of a blade allows the outer zones to expand. The works of Barz (3), Skoglund (20), Stodola (21), and Timoshenko (25) all indicate that, in the outermost zone, the tangential stresses due to rotation are lowest, while the radial stresses go to zero. Therefore, there cannot be a greater unit strain in the outer zones than in the inner, since in an elastic body the unit changes in dimension must be proportional to the stresses. The total elongation of the rim may be greater than that of the central zone, but the mere existence of such differential elongation cannot account for observed blade vibrations, because all rotational stresses are tensile.

It is said also that the blade needs to be tensioned more for higher than for lower speeds (6, 9, 10, 12). Whether this requirement is due to the increased rotation alone, or to the increased heat of cutting, is usually not stated. Barz (2) has shown that there are several critical speeds at which blades tend to vibrate. At speeds slightly higher or lower than these critical speeds, blades vibrated with smaller amplitude. Whether tensioning alters these critical speeds is open to question. In any event, it seems best to avoid them.

Several investigators have explained how a blade, termed loose in the center because of a relatively highly tensioned state, becomes straight and rotates in a plane when it reaches the proper speed. They say that the tensioning and consequent dishing of the blade have overcome the centrifugal force. It would perhaps be more appropriate to say that the rotational stresses have balanced the stresses induced in the middle zones by the tensioning, and have augmented the stresses near the rim.

It may be questioned whether too much reliance has been placed on tensioning as a panacea without sufficient study of its limitations. Many explanations of tension and of the behavior of rotating saw blades seem to be intuitive, without adequate foundation in theory or in experiment. "But intuition is a weak reed upon which to lean when rotation is under consideration" (23).

Another possibility for improving thin blades is to modify their geometry to make them stiffer. For example, tapered blades are in use for large headsaws, shingle saws, and other operations requiring a deep cut with small kerf. Nevertheless, the difficulty of manufacturing such tapered blades and the general preference for gang saws have restricted their development.

Expansion apertures have been placed in circular blades by the manufacturers to reduce thermal stresses during brazing or other operations that generate heat near the rim, to reduce thermal stresses during sawing, and to augment the cooling effect of the air. Barz (3) has pointed out that the cooling effect is important. If the annulus in question does not reach so high a temperature with the apertures as without them, there is obviously less expansion. The number, shape, size, and position of expansion apertures become of great interest in thin blades. If the variable thermal state could be rendered harmless and disregarded, one great obstacle to the use of such blades would be overcome.

Tooth geometry, tooth wear, and cutting forces are especially important in thin blades. Small forces may be associated with low friction, low thermal gradients, and little tendency to buckle. Attainment of small cutting forces has been the object of studies by several investigators. Reineke (15) showed how research in tooth geometry might lead to the use of thinner blades. Harris (8) pointed out the importance of tooth angles, gullets, number of teeth, and other factors, and led the way to further research. Endersby (5) studied the effect of tooth angle on the blunting of planing knives. Franz (7) studied chip formation and cutting forces at various cutting angles with a dry and a lubricated stationary knife. The correct application of these results requires more than a knowledge

Table 2. PHYSICAL CHARACTERISTICS OF SOME 16-IN. DIAMETER EXPERIMENTAL BLADES[a]

Blade design-ation	Blade Measurements					Teeth				
	Hardness, Rc	Hub thickness in.	Nominal hub radius in.	Rim thickness in.	Nominal angle of taper, deg.	Number	Cutting angle, deg.	Sharpness angle, deg.	Clearance angle, deg.	Depth of gullet, in.
1	2	3	4	5	6	7	8	9	10	11
5		0.125	4.31	0.033	1°c/d/	30	40			0.69
6		0.125	4.31	0.034	1°c/d/	26	40			0.69
9		0.125	5	0.035	0.75d/	30	40	42.5	7.5	0.56
13		0.125	5	0.032	1d/	30	40	42.5	7.5	0.44
15		0.125	5	0.032	None	30	40	42.5	7.5	0.44
9		None	None	0.049	None	30	40	42.5	7.5	0.44
2		0.125	5	0.032	0.25d/	30	40	42.5	7.5	0.44
31		0.125	2.75	0.032	0.75d/	30	40	42.5	7.5	0.44
32b/	47-49	0.122	5	0.032	0.75d/	30	40	42.5	7.5	0.44
33b/	47-49	0.122	5	0.032	0.75d/	30	35	47.5	7.5	0.44
34	47-49	0.122	5	0.032	0.75d/	30	40	42.5	7.5	0.44
35	47-49	0.122	5	0.032	0.75d/	30	35	47.5	7.5	0.44
36	47-49	0.122	5	0.024	0.75d/	30	35	47.5	7.5	0.44
51	48-50	0.122	5	0.032	0.75d/	30	35	47.5	7.5	0.44
50g/	48-50	0.122	5	0.032	0.75d/	30	35	47.5	7.5	0.44
55E	48-50	0.122	5	0.032	0.25d/	30	35	47.5	7.5	0.44
71f/	48-50	0.122	5	0.032	0.17d/	30	35	47.5	7.5	0.44
72f/	48-50	0.122	5	0.032	0.17d/	30	35	47.5	7.5	0.44
73f/	48-50	0.122	5	0.032	0.17d/	30	35	47.5	7.5	0.44
74f/	48-50	0.122	5	0.032	0.17d/	30	35	47.5	7.5	0.44

a/ All blades except 32 and 33 made of saw steel of composition C 0.67, Mn 0.30, Si 0.30, Ni 0.75, Cr 0.60, Mo 0.18.
b/ Blades 32 and 33 made of 17-7 PH stainless steel.
c/ Average taper of hyperbolic profile.
d/ Tapered on one side only.
e/ Symmetrically tapered on both sides.
f/ With expansion apertures.
g/ Chromium plated, 0.005 in. thick.

Fig. 2.—Typical asymmetrically-tapered experimental blade.

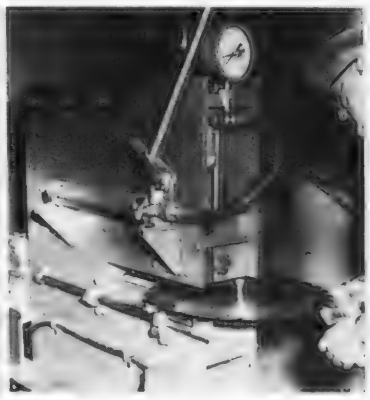

Fig. 3.—Hydraulic tensioning machine.

of the principles. As with blade flatness, suitable tooth geometry requires suitable techniques and equipment. It is one thing to adopt a suitable design of tooth; it is quite another to attain the precision of angles and character of ground surface required for improved performance.

Space limitations prevent mention of many other problems of circular saw blades and sawing, but an excellent report on the status of research in many of those problems has been prepared by Lubkin (13).

Experimentation

The experimental work was undertaken to solve specific problems in sawing pencil slats. Blade flatness, vibration, thermal effects, blade geometry, and tensioning were selected for study.

Equipment: In its present form, the equipment consists chiefly of special blades and a special machine for testing them. Fig. 2a shows a typical experimental blade—diameter 16 inches, thickness at rim 0.032 inch, and thickness at hub 0.125 inch. The 30 teeth are tipped with tungsten carbide. Fig. 2b shows a cross-section of a generalized blade that can be of any thickness, angle of taper, and diameter of hub.

Table 2 gives the geometry and other characteristics of some experimental blades. Most were tapered, either on one side only, that is, asymmetrically, or on both sides, symmetrically. The central, parallel-sided zone of such blades constitutes an integral hub or flange.

The teeth were always ground to concentricity and equiangular spacing. A recess was ground in each tooth, and a tungsten carbide tip was attached by an electrical resistance brazing method described by Wilcox (26). This method avoids overheating or distorting the thin blade. The brazed, renewable teeth were adopted chiefly to maintain a constant diameter, rim thickness, and cutting speed. In addition to the brazing method reported, a technique was developed whereby the teeth could be accurately ground to the geometry and surface finish desired. A slow rate of blunting may be expected from tungsten carbide teeth with a large sharpness angle (Fig. 2) and with a smooth cutting edge, judging by the research of Endersby (5).

Standard tools for flattening and tensioning circular blades were used in the initial experiments. Later a tensioning machine, which resembled a band-saw stretcher, was built (Fig. 3). It comprises a heavy frame and the means for horizontally centering a blade up to 2 feet in diameter so that any selected annulus may be pressed between a pair of power-driven, hardened steel rolls. A hydraulic hand pump, a pressure gauge with maximum hand, and a ram, permit the rolls to exert as much as 20,000 pounds force while slowly rotating the blade along the selected annulus. Each roll is $\frac{5}{8}$ by $3\frac{1}{2}$ inches, with its rim curved on a 9-inch radius. The shape of the rolls and the force on them produce a pressure sufficient to deform the metal plastically, and leave residual stresses similar to those induced by hammering, but without the hammer marks.

The experimental machine for testing blades while idling or sawing comprises the following: a horizontal belt conveyor for blocks; a feeding mechanism variable to 75 feet per minute; a pulley-driven arbor with two thick, 16-inch-diameter blades for edging all blocks; and two additional arbors in series, each for a single experimental blade, as shown in Fig. 1. Each of the blades in turn can saw one slat from the advancing block. Both arbors are driven directly by motors. One of these operates at 3,450 to 3,600 rpm; the other has variable speeds from 1,000 to 5,000 rpm.

Instruments were developed to measure the deviations of the blade while idling or sawing. One type of device measures a varying electrical capacitance. A fixed, circular, ½-inch-diameter plate, called a probe, and the blade constitute a capacitor whose capacitance is a function of the intervening distance. The probe is maintained at 0.100 inch from a plane of rotation of the blade and at a radius of $1\frac{1}{16}$ inches. If a small area of the annulus changes its distance from the probe by a small fraction of the normal distance, say 1 percent or 0.001 inch, the corresponding change in capacitance is almost linearly proportional and can be measured accurately. The amplified current is fed to three devices: a milliammeter whose needle indicates the average deviation of the annulus from the reference plane; a device to disconnect all motors if the blade deviates 0.010 inch for about 1/6 second; and a cathode ray oscilloscope. The oscilloscope is connected to a magnetic transducer, which senses

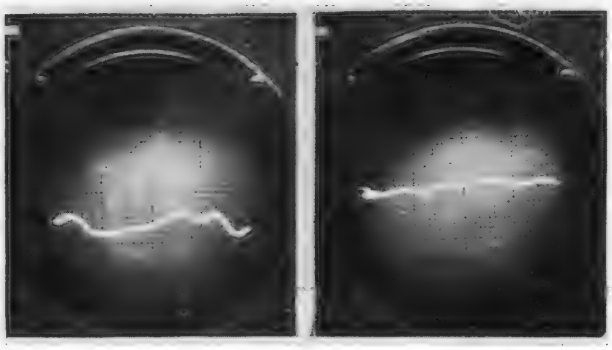

Fig. 4.—Oscillographs of a flat blade, 34, (right) and of one which is not flat, 31, (left) both rotating at 3,450 rpm.

Table 3. EXPERIMENTAL BLADES WITH EXPANSION APERTURES

Blade no.	Expansion apertures	
	Number and shape	Position
71	none	
72	6 slits, 1/32 x 1 in., terminating in hole, 1/8-in. diameter	Radially from intersection with every fifth gullet
73	30 holes, 1/4-in. diameter	Below base of each tooth, equidistant from adjacent gullets
74	30 slits, 1/4 x 1 in., rounded at ends	Radially from below base of each tooth, equidistant from adjacent gullets

each revolution of the arbor. Thus the oscillograph pattern along the horizontal axis represents the position of the selected annulus during an integral number of revolutions at any speed. By calibration, one small square in a vertical direction corresponds to about 0.001 inch deviation of the blade from the plane of reference. If the blade is perfectly flat, its oscillograph is a straight line along the horizontal axis. If the blade is dished in or out, but retains radial symmetry, the oscillograph remains straight but moves vertically away from the horizontal axis. If the blade has a twisted, undulating, or bumpy contour, or if standing waves are induced in it, the oscillograph will be a wavy line, as if the blade had been rotated against a fixed-dial gauge and a graph had been made connecting a large number of measurements around the selected annulus. Vibrations that do not repeat each revolution result in two, three, or more graphs visible simultaneously.

Experimental Work: *Blade Flatness:* It is necessary to define and measure flatness, not only for blades with parallel sides but also for those with tapered profiles. The word "flat" obviously cannot apply to the contour of the blade faces. In this study it is applied to an undistorted blade, that is, a blade ground from a flat plate without residual stresses. Thus, in a flat blade of symmetrical cross-section, the median surface would be a plane. In a flat blade tapered only on one side, the other side would be a plane. For the purpose of these experiments, a blade with a maximum of 0.003 inch deviation from a plane of reference at an annulus about 1 inch from the rim was called "flat."

A straightedge was used to measure flatness during the initial experiments. This method has been described in detail in many manuals on the maintenance of saw blades (6, 12, 18). Although it is a rough test of flatness, it does not measure flatness with the precision required. A dial gauge was used to greater advantage. The saw blade was mounted on an arbor between collars and tightened with a nut, so that the sides of the central part or hub of the blade were tightly clamped between flat plates at right angles to the arbor, and therefore acted as planes of reference. By mounting the dial gauge adjacent to the saw, it was then possible to measure the deviation around any desired annulus at as many positions as desired. This method showed any distortion that needed to be removed.

To learn whether the blade was stable, that is, whether it remained flat during idling and also during sawing, it was necessary to provide means of dynamic measurement. After the installation of the electronic instruments already described, a blade could be mounted on an arbor and easily tested for flatness by first turning it manually and then rotating it at various speeds. All experimental blades were tested in this way after each stage of manufacture, including the attempts to flatten them, the brazing of the tungsten carbide tips, and so forth. The traces produced on the oscilloscope by each rotating blade were photographed to provide a permanent record.

Hammering blades was one method used to flatten them. For example, blades 9 and 12 (Table 2) were hammered. In the beginning, it was not possible to saw slats with these blades for more than a few seconds. When the more accurate testing method became available, the same blades were hammered again. When they reached the desired degree of flatness, they were used again in sawing experiments. These flattened blades sawed slats during several runs of about 30 minutes at a feed speed of 75 feet per minute.

A leverage sufficient to stress a blade beyond its yield point was sometimes applied to flatten twisted blades while they were on the arbor. Bumps that could not be removed by this method were flattened with a rawhide hammer.

In another method, the blade mounted in a lathe. While the blade is slowly rotated in a special chuck, a roll mounted in the tailstock is brought into contact with the blade, with force sufficient to bend it beyond its flat position. Upon removal of the force, the blade returns, elastically, part of the distance through which it was bent.

Although these methods were successfully employed to flatten many experimental blades, it was thought desirable to study the manufacture of several blades from the original steel plate stock to see whether they could be manufactured in a flat condition. Such a study was made for blades 32 to 35, which were made of two types of steel, as shown in Table 2. The heat treatment employed for hardening and tempering these blades was appropriate for the particular steel. In all other respects, the four blades passed through the same manufacturing operations. They were placed in clamps during the tempering, and subsequently were ground with great care, including precautions to avoid local heating. These efforts resulted in three blades that were well within the desired tolerance of flatness, while the fourth, 32, exceeded the tolerance by only 0.001 inch.

Fig. 4 shows oscillographs of blades 31 and 34, tipped with tungsten carbide, but otherwise left in the original manufactured condition. Blade 31 has the smaller hub and was made without the special procedures described for blade 34.

Vibration: The term "vibration" is used herein to describe any behavior of a rotating blade that results in two or more simultaneously visible oscillograph patterns, or in any marked difference of the oscillograph pattern from the static distortion.

All untensioned experimental blades were mounted on the arbor and rotated at various speeds from about 1,000 to 5,000 rpm. As the speed was increased from 1,000 to about 3,100

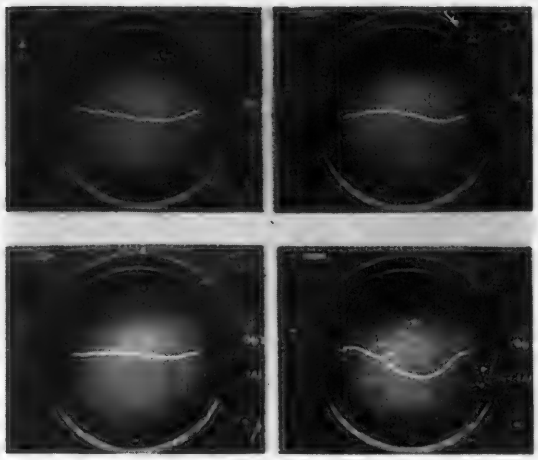

Fig. 5.—Oscillographs of blade 34 showing effect of rotational speed on vibration. Top left, 2630 rpm; right, 3250 rpm; lower left, 3470 rpm; right, 3190 rpm.

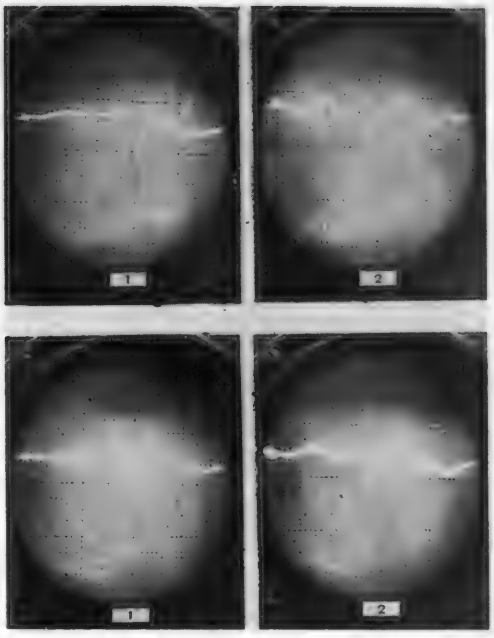

Fig. 6.—Effect of tension on resistance of blade 34 to oxyacetylene flame at 3,450 rpm. Top, not tensioned; bottom, tensioned. No. 1, flame; No. 2, no flame.

rpm, some blades became slightly flatter along part of the scanned annulus. As the speed was increased above 3,100 rpm, all the tapered blades exhibited a gradually increasing deformation. Complex vibrations, indicated by complex oscillograph patterns, sometimes occurred. At speeds of about 100 rpm higher, a sudden change took place. The vibrations ceased and the oscillograph assumed a new form that indicated a marked improvement in flatness. As the speed was increased further, the phenomenon recurred at several speeds. These results resemble those of Barz (2).

The oscillographs of a flat blade rotating at several speeds are shown in Fig. 5. Since this blade was asymmetrically tapered, it tended to dish toward the tapered side, as shown by higher average position of the graph at higher rotational speeds.

Tensioning a blade to improve its stability at desirable speeds has been practiced, as already mentioned. Results of rotating experimental blades after tensioning will be described under the tensioning experiments.

Thermal Effects in Static and Rotating Blades: Experiments were made to measure temperature and observe its effects. For static tests, the blade was laid upon a perforated block of wood with thermocouples attached to recessed springs. Wires passed out the bottom through a multiple-position switch to a potentiometer. The thermocouples constitute measuring stations 1 inch apart along several radii.

Some steel blades 8 inches in diameter and about 0.50 inch thick were tested. These were unplated; plated with chromium; and plated with copper, nickel, and chromium. The copper was 0.0001 inch. this on each face. These blades were heated by the friction of a ½-inch diameter wooden dowel rotating in a drill press. Similar tests were made when the source of heat was an electric soldering iron with molten solder at its extremity in contact with the blade.

The temperature of all blades rose rapidly near the heat source and slowly elsewhere. The temperature distribution in all blades was nearly the same. Although the diffusivity of copper is about ten times that of the steel, the thin-plated layer did not contribute appreciably to the diffusion of heat. Blades with a polished surface absorbed heat somewhat more slowly than did unpolished blades. The differences in rate of temperature change of all the blades can be attributed almost entirely to their surface characteristics.

After each blade had reached a steady state of temperature, or a maximum of 400° F. under the heat source, a 0.60-inch. orifice nozzle emitting compressed air at 60 psi was directed at the area of contact. This can be likened to the air flow past the blade during rotation. The cooling effect of the air was very striking, and suggests the possibility of better air cooling by modification of blade geometry and surface characteristics.

For a rotating blade, the temperature reached by various annular zones was measured by special paints, of various melting points, applied to the back of the blade in radial streaks. The blade was heated by an oxyacetylene flame held 1 inch distant from the front, tapered side, at any chosen radius. When the flame was applied below the gullets ($r = 7.5$ in.) of any asymmetrically tapered blade, the rim tended to move laterally toward the tapered side. This outward dishing resembles the displacement induced by the transverse moment of the rotational forces. Distortions already existing in the blade tended to increase. Additional heating induced larger deflections or buckling of the heated zone. Fig. 6 shows the oscilloscope trace for blade 51 with and without the oxyacetylene flame. Fig. 7 shows the temperature distribution at buckling. When the water spray simultaneously impinged on the blade, the oscillations subsided immediately.

The blade was also heated by the friction of a wooden stick pressed against the front, tapered side. For friction at $r = 7.5$ inch, the rim dished outward and its distortions increased. Severe buckling followed. For friction at $r = 5.0$ inches, the rim dished inward. Distortions already existing in the blade tended to decrease. Heating in the middle zone is similar in effect to mechanical tensioning. Barz (3), Lindholm (11), and Sugihara (22) have used this analogy to estimate the state of stress induced by tensioning.

When the water spray was turned on during the rubbing, a lubricating effect was felt immediately. Any oscillations subsided. Fig. 8 shows the temperature distribution in blade 34, with and without the water spray during frictional heating.

Other methods of counteracting adverse thermal gradients were studied. Among these were tensioning the blade and putting expansion apertures in it. These methods will be described later.

Blade Geometry: Some criteria for suitable blade geometry can be described as follows:

1. The blade must deliver the necessary torque to the teeth without vibrat-

ing or buckling. It must resist lateral deflection of the teeth caused by slight deviations in the direction of feed or by nonuniformity of the wood on each side of the blade, such as occurs when sawing parallel to the growth rings.

2. The thickness of a tapered blade must not increase radially enough to split the slat from the block or to pull the block outward, away from the fence. The taper must not cause the slat to force the blade toward the fence.

It must be remembered that the slat, as it is sawn from the block, is advancing along the tapered blade toward zones of increasing thickness. As soon as the blade thickness has increased more than the clearance or set of the teeth, the slat will begin to press against the side of the blade. The opposite forces thus generated will tend to make the wood deviate outward and the blade inward.

3. Heat will be generated by the friction caused by the advancing slat rubbing against the blade. The temperature and thermal gradient will depend on thickness, grain, and other characteristics of the wood, and on taper, surface characteristics and rotational speed of the blade. Tooth geometry affects the generation of heat near the rim. These several factors must be regulated so as to generate the least possible heat.

As in other tests, the oscillograph indicated the position of the blade near the rim, while idling or sawing. The ammeter gave information regarding the energy requirements. The examination of the blade and the wood for rubbing, the measurement of the temperature of the blade, the measurement of slat thickness, and other visual observations facilitated the evaluation of experimental blades.

Blade 5, which had 1 degree of taper on one side for 2.5 inches was first tried to find the optimum taper. Various experiments in sawing slats at slow speeds showed that the taper was not excessive. Blade 6, with original taper of 1.5 degrees, was then tried. Severe heating occurred in an annulus from r = 3.5 to 3.9 inches as indicated by the rubbing of the slat against the blue lacquer previously applied to the surface of the blade. Excessive taper also resulted in splitting of the slat off the block before the upper rear corner could be sawn. This blade was reground several times. By such experiments, the best taper for sawing pencil slats with an asymmetrical blade was found to be 0.75 degree. The maximum allowable taper was determined to be 1 degree. The tips of the teeth protruded 0.1 inch from the top of the block.

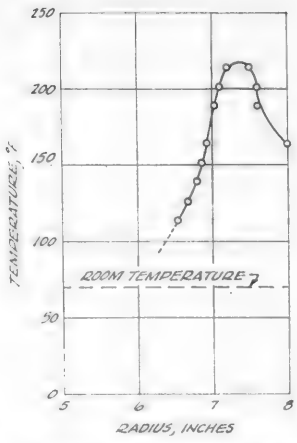

Fig. 7.—Radial temperature distribution at time of buckling in blade of Fig. 6.

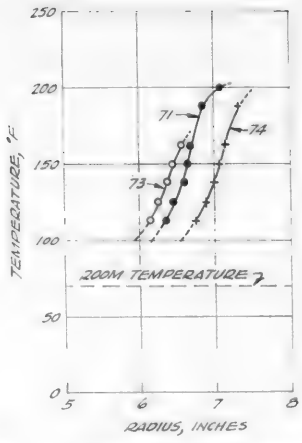

Fig. 10.—Radial temperature distributio in symmetrically-tapered blades at stead state.

Some studies were made of the path that the slat took as it was deflected from its straight-line forward motion. It can be shown that the slat first clings to the side of the blade and then moves away from it in a line tangent to a hyperbola along the section of the blade parallel to the bed of the machine. It was found that the blade could be strengthened by tapering parts of it, especially near the hub, hyperbolically rather than linearly. This subject has not yet been pursued, but it is worthwhile mentioning as an example of geometric strengthening.

Since the depth of cut was constant, the integral hub, always about 0.125 inch thick, was made larger in diameter on successive blades, to stiffen them. The collars were made 1 inch less in diameter than the integral hub in order to clear the bed.

The experiments with tooth geometry were made to utilize information already obtained by others. As the experiments progressed, the gullet size was reduced to hold a chip sawn at a maximum feed rate of 75 feet per minute for a 30-tooth blade, rotating at 3,450 rpm, or maximum bite per tooth of 0.009 inch. The volume of wood removed for a kerf of 0.050 inch is 1.17×10^{-3} in^3. Since the thickness of the blade is 0.032 inch, neglecting taper, the gullet area ought to be 0.11 in^2, when the factor 3 recommended by Harris is used (8).

The cutting angle of the tooth was reduced from 40 degrees to 35 degrees during the course of the studies. Measurements of slats sawn during various experiments and observations of the oscilloscope indicated that the lower angle caused less deviation of the tooth in wood sawn parallel to the growth rings. Also, it was possible thus to increase the sharpness or wedge angle from 42.5 to 47.5 degrees. The advantages of a high sharpness angle have been described by Endersby (5).

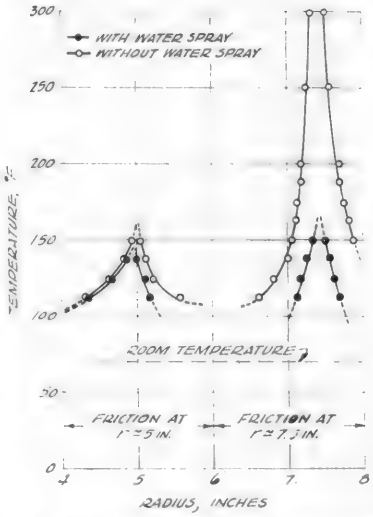

Fig. 8.—Radial temperature distribution induced by stick friction in blade 34 at steady state.

Tensioning: The tensioning was first done by hammer and anvil in connection with straightening the blade. Blades 5, 6, 9, and 13, for example, were so tensioned. In a tapered blade it is difficult to use the straightedge technique to measure tension.

Upon completion of the hydrauli tensioning machine, concentric annuli could be rolled into a blade at an radius. The total force on the rolls to give adequate tension to certain blades was about 12,000 pounds.

A suitable radius for tensioning was chosen by pressing a wooden stic against the rotating blade in the mid dle zone. Such thermal tensioning, as it may be termed, resembles the so-called packing described by several authors, including Foyster (6) and Simons (18). It causes an asymmetrical blade to dish inward, that is, in the opposite direction to that caused by friction near the periphery. Suitabl radii for the tapered 16-inch blades

with integral hub, were found to be between 3.5 and 4.5 inches. Each blade was rotated at various speeds, and its oscillograph was studied. Tensioned blades became flatter, with few exceptions. The critical speeds of vibration were not always the same as before tensioning; the amplitude of vibration diminished.

The wooden stick previously described was pressed against the tapered side of the blade at a radius of about 7.5 inches. Temperatures up to 300° F. were created. If the rim of the blade vibrated with an amplitude of more than 0.003 inch, or moved that distance toward the tapered side, the blade was retensioned with greater force. If it remained substantially stable, it was considered suitable for a sawing trial.

There are several disadvantages to this method of testing for adequate tension. A thermal stress and a lateral force act on the blade simultaneously. Their combined effects are of interest, but it would be desirable also to analyze them separately. The experiments with an oxyacetylene torch, already described, permitted the creation of a thermal gradient without a significant lateral force. Fig. 6 shows the effect of the oxyacetylene flame on blade 51 before an after tensioning. The thermal gradient was the same as shown in Fig. 7.

Some exploratory studies were made of four blades with expansion apertures. Since there is an infinite number of possible types of apertures (generally called expansion slits or holes), these blades represent only a convenient beginning of such experiments. The necessary width of each aperture to permit free expansion of the blade in a given zone can be calculated from the blade geometry, the thermal properties of the steel, and the expected rise in temperature. For the experimental blades with 30 apertures, this width at a radius of 7 inches was calculated to be 0.002 inch for a temperature rise of 200° F. The actual experimental expansion apertures were made much larger for simplicity of manufacture. Details of the apertures in these four experimental blades are given in Table 3.

The four untensioned blades were painted on one side with temperature-sensitive lacquer, successively mounted on the arbor, rotated at 3,450 rpm, and heated by the oxyacetylene flame. After each experiment, the blade was removed and examined for the temperatures reached by various annular zones.

The dynamic behavior of these blades with time is shown in Fig. 9. All four blades exhibited a trembling motion between 4 and 6 seconds after the flame was applied. The temperature gradient was then essentially the same for all four blades.

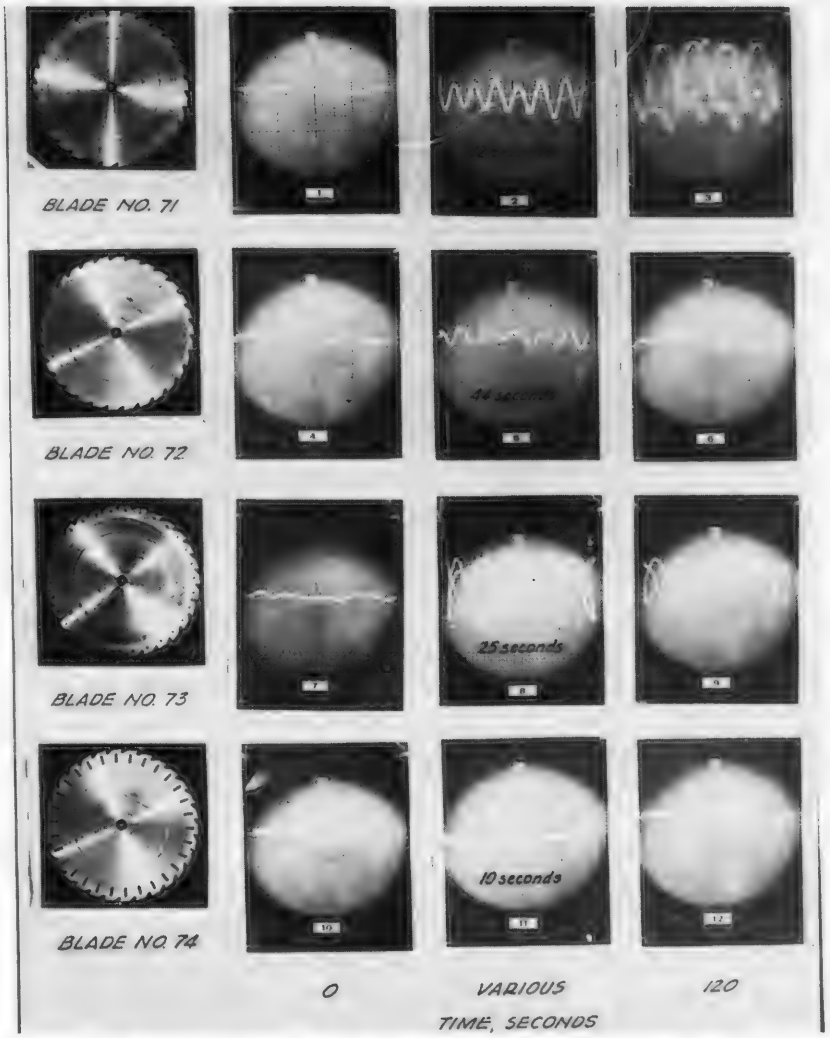

Fig. 9.—Dynamic behavior of blades with and without expansion apertures under the influence of oxyacetylene flame.

Definite vibrations were first in evidence in the blades at times varying from 12 to 44 seconds, with the exception of blade 74, which showed no vibration after the initial trembling. The vibrations developed by blades 71 and 73 were sustained for the duration of the test, while those developed by blade 72 died out almost immediately.

The temperatures after 3 minutes are shown in Fig. 10. The difference in maximum temperature achieved is attributed to the slightly different times of exposure to the flame, and to the cooling effect of the turbulence created by the apertures.

Application of Results: From time to time, blades of selected characteristics were used to saw slats experimentally at various rotational and feed speeds. Several runs of a few to 30 minutes were made, during which the blades functioned without significant heating or vibrations. Water spray kept the blades cool and clean, and permitted certain otherwise unacceptable blades to function. In general, all these studies pointed to the efficacy of making, testing, and using thinner circular saw blades.

On the basis of these results, a pilot machine using tapered blades was developed for the manufacture of pencil slats (Fig. 11). It consists essentially of a variable feed, top and botton planer heads, and two parallel-sided, 16-inch, tungsten-carbide-tipped ripsaws to make the block 2.63 inches high by 2.755 inches wide. Thereafter, the blocks pass 10 tapered, 16-inch, tungsten-carbide-tipped blades like 51 or 65E described in Table 2. Each blade is placed in front of the preceding one, and offset so that it saws a single slat. Each blade has a direct-drive, 5-hp motor that rotates at 3,450 rpm under full load. Magnetic transducers instead of capacitance probes are provided for each blade to permit the constant observation of its dynamic

behavior. Furthermore, they protect it by automatically switching off all motors, including the feed, whenever the deflection exceeds a permissible limit. The blades can be constantly sprayed with liquid. A transparent plastic hood covers all the blades. This machine will be used to evaluate blades on a production basis.

Initial trials resulted in the sawing of 11 slats with an average thickness of 0.207 inch. The average kerf was 0.048 inch. The decrease in kerf represents an increase of 10 percent in product from the same raw material.

Conclusions and Recommendations

1. Thin, tapered blades can and should be made and maintained flat without hammering.

2. Vibration of a rotating blade can be prevented by proper manufacturing, by avoiding extraneous vibrations, including axial movement of the arbor, by avoiding critical speeds of rotation, by using large and accurate collars, and by avoiding objectionable thermal stresses.

3. Centrifugal force may cause vibration in a distorted or otherwise unbalanced blade. In other respects, centrifugal forces are beneficial because they tend to flatten the blade, increase its natural frequency of vibration, and counteract compressive thermal stresses near the rim.

4. Thermal stresses caused by heating near a thin rim should be prevented. Suitable teeth reduce cutting friction. A flat, smoothly rotating blade avoids excessive lateral rubbing. Cooling the outer zones or heating the inner zones reduces the thermal gradient. Expansion apertures cool the blade and relieve compressive stresses near the rim. Tensioning counteracts such stresses.

5. Metallurgical studies should be directed toward a saw blade regarded as a vehicle for replaceable teeth.

6. Hydraulic pressure rolls are better than a hammer for controlling the position, magnitude, and uniformity of tension.

7. The stresses induced in a blade by tensioning have been explained in part by other investigators. A theory to describe all the ramifications of tensioning can be developed only after the tensioning stresses can be measured. Nevertheless, it is clear that tensioning induces tangential tensile stresses in the outer zones, thereby counteracting compressive thermal stresses. It does *not* compensate for the expansion of the rim due to centrifugal force, but, on the contrary, augments it.

8. Thin blades can be tipped with tungsten carbide without danger of annealing or buckling. The diameter and the rim thickness of a tapered blade can thus be kept constant.

9. Thin, tapered, carbide-tipped circular blades, mounted on a suitable machine, can saw incense-cedar to a depth of 2.6 inches with a kerf of less than 0.050 inch at 75 feet per minute.

The studies described herein are continuing. More research in circular saw blades and other phases of wood machining is needed to create a basis for improvements in the sawmilling and remanufacturing industries. To provide blades and machinery for specific operations, industrial research and development also are essential.

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INDICES OF QUALITY...

Vibrational Properties of Wood

B. A. Jayne

Vibration offers a promising method for non-destructive testing of wood. The author shows that the characteristics of clear wood can be estimated to an accuracy heretofore considered unattainable.

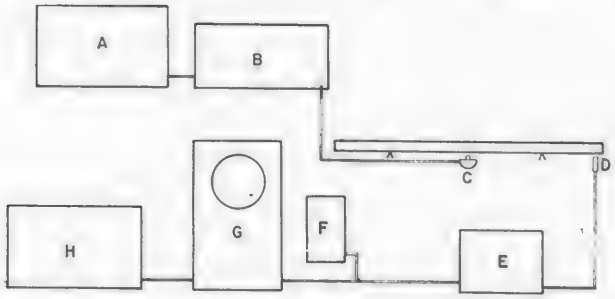

Fig. 1.—Apparatus used for non-destructive testing. (See text for meaning of symbols.)

WOOD, WITH ITS INHERENT VARIATION, has been severely penalized when subjected to the competition of structural materials possessing more uniform mechanical properties. One need look no further than its waning market in competition with other building materials and the over-design so often characteristic of wood structures. This situation stems largely from structural design data for wood that calls for a reduction in the strength of every piece of lumber to a value virtually equivalent to that of the weakest piece of its particular grade. Such practices are necessary currently to allow for the inherent strength variation of wood.

A knowledge of the characteristics of each piece of lumber could do much to avoid this undesirable situation. Material of superior quality could then be designated for critical uses, and stock of poorer quality could be relegated to uses where strength and stiffness are not as important. The need calls for a non-destructive test that can be used to estimate the stiffness of wood in flexure and compression as well as bending and maximum crushing strength.

The relation of modulus of elasticity to the resonant frequency of a non-destructive vibrational test has been known for more than 100 years. According to Todhunter and Pearson (5), Savart, a French physicist of the early 19th century, was one of the first scientists to compute the modulus of elasticity of an iron bar from the resonant frequency of a longitudinal mode of vibration. A short time later Lagerjhelm [see Todhunter and Pearson (5)] compared Savart's value of 1033 with his own experimental determination of 1070 from the results of static tests of iron in tension.[2] It is believed that this marks the first attempt to compare elastic constants as computed from dynamic and static mechanical tests. Since this early attempt, however, numerous investigators have made similar comparisons using not only the longitudinal mode of vibration to estimate the modulus in compression and tension but also utilizing the resonant frequency of flexural modes to compute modulus of elasticity in bending and the torsional mode for calculation of the shear modulus. For wood in particular, the work of Kitazawa (4) and later Bell *et al* (1) has demonstrated clearly the possibility of using vibrational characteristics for estimating the static modulus of elasticity.

However, just as a complete description of the static mechanical properties of a material is not restricted to modulus of elasticity alone, the dynamic mechanical characteristics of a material are specified by several indices other than the natural frequencies of vibration. One of these is dynamic energy loss. An object set into resonance is maintained in motion by continued application of a periodic force. If the exciting force is removed, vibration gradually recedes at a rate that is logarithmic with time. This decay or damping of vibration can be expressed as the logarithmic decrement (δ), the slope of a free vibrational decay curve in logarithmic time, or as $\Delta\omega$, work loss during vibrational decay. Energy loss of a vibrating system can be expressed also as Q, the sharpness of resonance of a vibrating system which is related mathematically to δ and as tan ϕ, the phase angle between stress and strain. It can be shown mathematically that these measures are closely associated with the static creep as well as the stress relaxation characteristics.

Studies of the mechanical properties of plastics and textiles, both of which are polymers and as such resemble wood, suggest that energy loss is due in large part to the configuration of their constituent molecules. The frequency and temperature sensitivity of this property suggests that molecules of several lengths having different types of intermolecular associations may be involved during deformation. Due largely to the empirical nature of the static mechanical properties, such as those obtained from the data of load-deformation tests, it has not been possible to obtain exact relationships with measures of dynamic energy loss. Nevertheless, its close association with static non-elastic characteristics suggests the possibility of statistical relationships heretofore unrecognized.

Recently, Galginatis *et al* (2) reported an empirical relationship between the maximum crushing strength of short specimens of wood and the quantity $\frac{D\delta}{f}$, where D equals density and f and δ are resonant frequency and logarithmic decrement, respectively, at the first harmonic of longitudinal vibration. The regression exhibited an exceptionally high degree of correlation. Furthermore, these investigators were able to demonstrate the effectiveness of logarithmic decrement for estimating glue-bond quality in wood laminates. This type of non-destructive test of laminates also has been reported by Jayne (3).

The existence of a few exact relationships between the static and dynamic mechanical properties coupled with the fact that both involve force and its resultant deformation strongly

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[1] A contributed paper received June 1959.

[2] Todhunter and Pearson (5) provide no units of measurement for the moduli of elasticity reported.

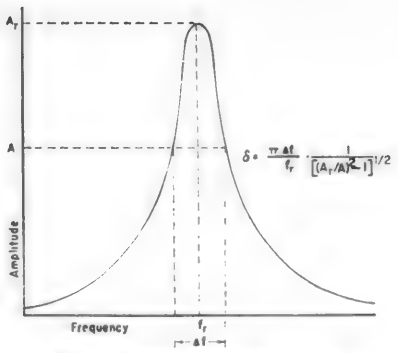

Fig. 2.—A frequency response curve.

suggests the existence of other valuable associations. Unfortunately, the empirical nature of many static mechanical properties virtually eliminates the possibility of fundamental relationships other than the various moduli. Nevertheless, empirical relationships may exist which can be defined statistically.

Since dynamic properties can be observed without inflicting damage to a member, they should have unlimited value for the classification of a structural material, such as lumber, into various categories according to mechanical properties. Currently, segregation is undertaken by grading; a procedure which at best can result only in broad classifications based on human judgment rather than technical data within the confines of statistical probabilities. On the other hand, non-destructively measured vibrational properties, which are closely associated with such properties as static stiffness and possibly bending strength of structural lumber, conceivably can act as a major supplement or in some instances as a replacement for visual inspection.

The benefits are obvious. Reduction in mechanical properties due to variability and conservative estimation of the strength of a wood species can be eliminated by measurement of the characteristics of each piece. Such a procedure should result not only in improvement in design practices currently followed with wood but also vastly improve its competitive position with other building materials. The design of laminated beams with various grades of lumber could be undertaken on a much more intelligent basis when the properties of each lamination are known before fabrication. For this use alone, such a method might pay for itself over a relatively short period.

Scope

A program of research was undertaken to verify the degree of correlation between the moduli of elasticity of wood measured dynamically and statically. The study provided also an opportunity to examine any relationships between static mechanical properties other than stiffness and characteristics determined vibrationally. A sample of clear Sitka spruce, representative of a wide range of specific gravity, was employed as experimental material. The resonant, damping, and static strength properties of several specimens were measured and compared statistically as well as by known mathematical relationships.

Experimental

Material: Specimens were selected from clear, straight-grained Sitka spruce. In order to insure a range of wood qualities the experimental stock was chosen from material which exhibited growth ring counts ranging from 6 to 30 rings per in. A total of 46 specimens were sawn to rough dimensions of 0.75 by 1 by 18 in., and conditioned to a uniform moisture content of 10 ± 1 per cent. Subsequently the specimens were machined to final dimensions of approximately 0.6 by 0.8 by 15 in. in such a manner that the growth rings were oriented perpendicular to the wide face.

Testing Apparatus and Procedure: Past research has shown that the most reliable and accurate measures of dynamic properties can be obtained by using electronic instruments for inducing and recording vibratory motion. The apparatus used in this investigation is shown diagrammatically in Fig. 1. It consisted of a speaker-driver unit (C) to induce vibration operated from the amplified output (B) of an ordinary audio-signal generator (A). Beam vibration was transduced to an electrical signal by means of a photoelectric cell (D); its output was amplified (E) and recorded on an oscilloscope (G) and voltmeter (F) arranged in parallel. A second audio-signal generator (H) was employed for frequency-matching purposes.

Each test specimen was supported above the throat of the speaker-driver approximately 0.15 in. Supports were placed at or near the nodes for the fundamental frequency to minimize external sources of damping. Using the driving audio-signal generator (A) the frequency of the speaker driver was adjusted to the fundamental resonant frequency of the specimen. Resonance was determined by observing the maximum voltage output of the photoelectric cell on either the oscilloscope or voltmeter. Its frequency was noted from a calibrated dial on the driving audio-signal generator. Knowing resonant frequency, weight, and dimensions the dynamic modulus of elasticity of each beam was calculated from:

$$E_b = \frac{0.00245 f_r^2 w l^3}{b d^3}$$

where E_b = dynamic modulus of elasticity in bending, lb. per sq. in.

f_r = fundamental resonant frequency, cycles per sec.

w = specimen weight, lb.

and b, d, l = breadth, depth, and length of specimen, in

The damping capacity of each specimen was measured by observing its amplitude response to a range of frequencies near resonance. A theoretical frequency response curve of a vibrating system is shown in Fig. 2 with the equation for computing logarithmic decrement. The solution of the equation requires a knowledge of the resonant frequency and width of the frequency response curve. Resonance was determined as noted previously. The width of the response curve at a predetermined amplitude, A, was obtained by adjusting the two audio signal generators to frequencies of equal amplitude, one on each side of the response curve. When placed on the vertical and horizontal deflection plates of the oscilloscope, these two frequencies formed a Lissajous figure that migrated through a series of forms at a rate equal to the difference frequency, Δf. To obtain the difference frequency, the migration was timed with an ordinary stop watch. In order to reduce the equation shown in Fig. 2 to a simplified form Δf was taken at either 0.500 A_r or 0.707 A_r.

Following vibrational testing, all specimens were tested to destruction in static bending on a Baldwin hydraulic testing machine operated at a platen speed of 0.078 in. per minute. Each specimen was loaded on its radial face over a 13-in. span. Values of fiber stress at proportional limit, modulus of rupture, and modulus of elasticity were computed from the results of these tests. A section for the determination of specific gravity (o.d. wt. and vol.) and moisture content was taken from each specimen immediately after completion of the static test.

Results and Discussion

The relationship of the dynamic and static moduli of the spruce specimens is shown in Fig. 3. Although there is some scatter about the solid regression line, the 95 per cent confidence limits as indicated by the dashed lines, are set at approximately ±100,000 lb. per sq. in. A correlation coefficient of 0.9 indicates that the regression accounts for more than 90 per cent of the variation. The plotted points are more heavily concentrated below the 45 broken line than above, hence, the dynamic test will yield a slightly highe

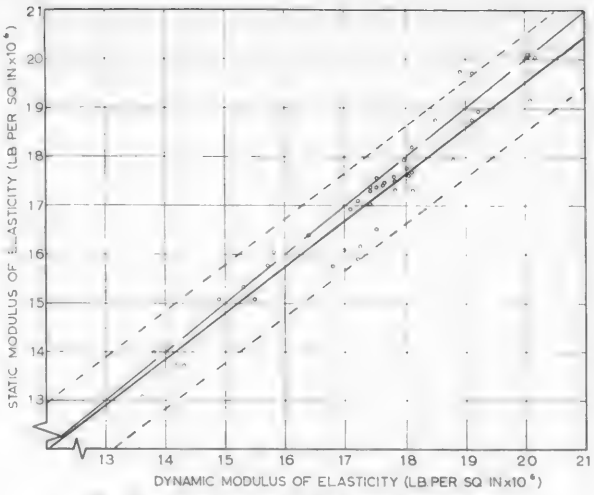

Fig. 3.—A regression of the static modulus of elasticity on the dynamic modulus.

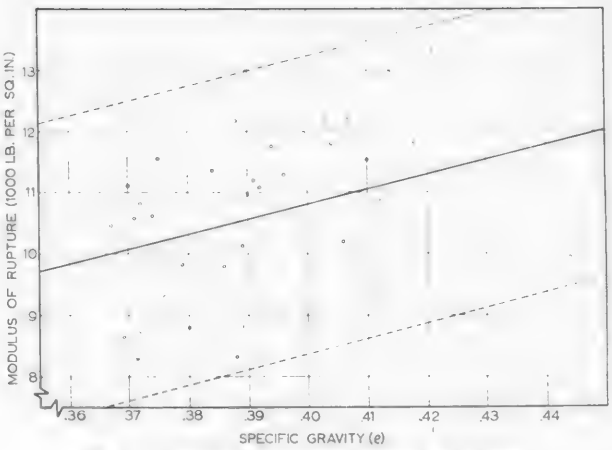

Fig. 4.—Relationship between modulus of rupture and specific gravity (ρ).

value of the modulus than its static counterpart. Other investigators (1, 4) have reported similar findings. Nevertheless, the lower confidence limit can be taken as a safe estimate of the static modulus.

The relationship of modulus of rupture to specific gravity (ρ) of the spruce specimens is shown in Fig. 4. Its 95 per cent confidence limits are set at $\pm$ 2,450 lb. per sq. in. and its correlation coefficient is only 0.267. Obviously the regression accounts for little variation in bending strength. On the other hand, a plot of modulus of rupture over the ratio of specific gravity to logarithmic decrement ρ/δ is characterized by a correlation coefficient of 0.824. The regression accounts for 68 per cent of the variability in bending strength and, as pictured in Fig. 5, the confidence limits are reduced to $\pm$1,450 lb. per sq. in. The regression in Fig. 6 demonstrates that the same quantity, ρ/δ, can be used to estimate the proportional limit stress to within approximately $\pm$1,000 lb. per. sq. in.

It is well known that mechanical properties of wood, such as bending strength and proportional limit stress, are closely associated with modulus of elasticity. It would seem, therefore, that the dynamic modulus might serve as a reliable indicator of bending strength. As shown in Fig. 7 the correlation possesses confidence limits of $\pm$1,000 lb. per sq. in. Furthermore, since modulus of elasticity is related directly and logarithmic decrement inversely to bending strength it appeared that a regression of bending strength on ϵ/δ offered possibilities to narrow even more the confidence limits for estimating modulus of rupture. The plot with limits of approximately $\pm$900 lb. per sq. in. is shown in Fig. 8. It should be pointed out that the independent variable, ϵ/δ, involves frequency, weight, dimensions, and the damping capacity of the material. For comparison the confidence limits of the regressions shown in Figs. 3–8 are listed in Table 1.

All values of the functions used as independent variables are subject to precise non-destructive measurement with only a minimum of conventional electronic equipment. It should be noted that the limits of estimate made it possible to categorize the material tested in increments of about 200,000 lb. per sq. in. for modulus of elasticity and approximately 1,800 lb. per sq. in. for bending strength.

Although the non-destructive data permitted a much more accurate estimate of mechanical properties of wood than density alone, it is paramount that the limits of variability be reduced even more so that the characteristics of wood can be estimated within more narrow limits. It is to be emphasized that the damping capacity of wood was measured at only the fundamental resonant frequency. Its measurement at harmonic frequencies together with information on the natural amplitude of vibration during resonance may provide the extra data needed to narrow significantly an estimation of bending strength.

Since stiffness primarily, but also bending strength, are the two criteria upon which beam design rests, a technique for their evalution non-destructively should receive wide use. The data shown herein demonstrates conclusively that both can be measured accurately and rapidly using conventional electronic equipment. The limits within which these characteristics were estimated attest to the superiority of the method over either visual inspection or the use of density alone as a criterion of strength.

Applicability

Currently, structural lumber is segregated into strength and stiffness classifications by visual inspection. Although this type of segregation is founded on years of experience backed by a great number of laboratory tests, it fails to take into account minute differences in wood structure. As is well known, these minute differences can have a tremendous effect on the mechanical properties of wood. It has been demonstrated that a vibrational non-destructive test has the capability of discerning these differences between pieces of wood that the eye or senses cannot perceive. Applied to structural lumber, the vibrational technique could account for "invisible" differences between pieces and provide precise classifications using critical mechanical properties as a basis. The result—each piece will be judged more nearly on its merits, not that assumed for the species.

The selection of stock for laminating may be a fertile area for exploitation of this technique. A knowledge of the characteristics of the components, will not only provide specific design data for each laminate but also make possible beam fabrication for a

Table 1.—CONFIDENCE LIMITS OF REGRESSIONS USED FOR ESTIMATING WOOD MECHANICAL PROPERTIES

Regression	*Confidence limits, lb. per sq. in.*
Static modulus of elasticity over dynamic modulus	$\pm$100,000
Modulus of rupture over specific gravity	$\pm$2,450
Modulus of rupture over the ratio of specific gravity to logarithmic decrement	$\pm$1,450
Proportional limit stress over the ratio of specific gravity to logarithmic decrement	$\pm$1,000
Modulus of rupture over dynamic modulus of elasticity	$\pm$1,000
Modulus of rupture over the ratio of dynamic modulus of elasticity to logarithmic decrement	$\pm$900

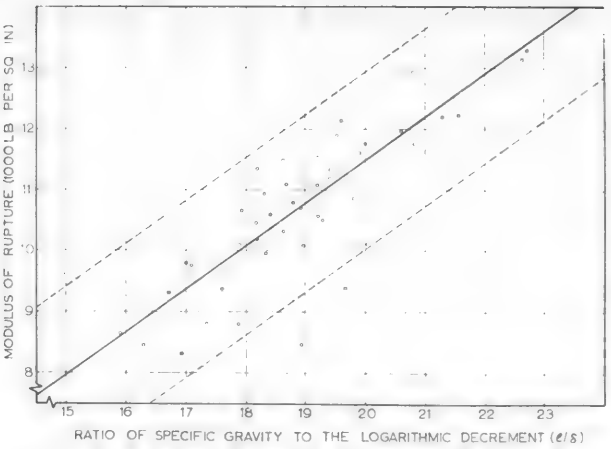

Fig. 5.—Regression of modulus of rupture on the ratio of specific gravity to logarithmic decrement (ρ/δ).

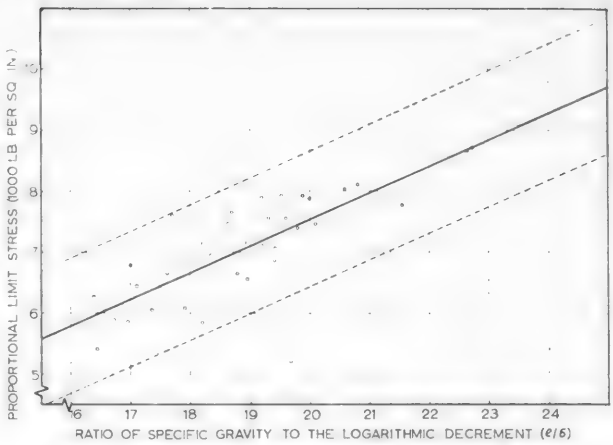

Fig. 6.—Regression of proportional limit stress on the ratio of specific gravity to logarithmic decrement (ρ/δ).

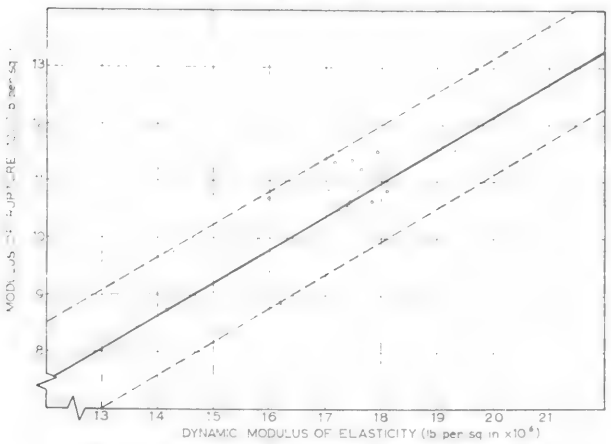

Fig. 7.—Regression of modulus of rupture on the dynamic modulus of elasticity.

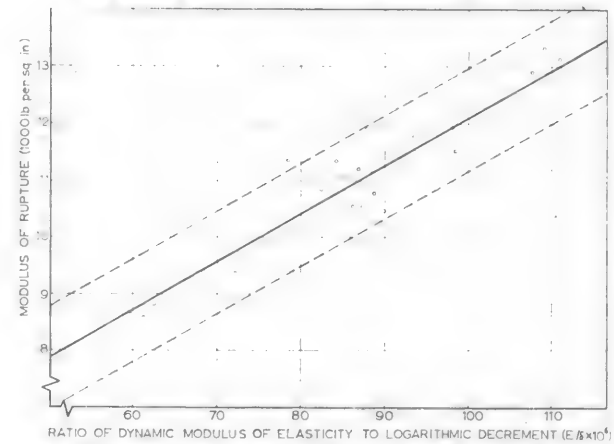

Fig. 8.—Regression of modulus of rupture on the ratio of the dynamic modulus to logarithmic decrement (E/δ).

particular use by designating appropriate qualities of stock for selected positions.

This technique for estimating mechanical properties non-destructively lends itself to use at some stage of lumber manufacture, preferably after drying and final machining. For greatest efficiency, a sensing system must be capable of estimating accurately the weight, length, width, thickness, resonant frequency, and damping capacity of each board. Measurement of each during manufacture with simple electronic equipment is within the realm of practicability. Weight can be measured by means of a simple load-cell system; dimensions can be determined using sensitive microswitches or linear differential transformers; and frequency and damping capacity can be sensed by means of a system similar to that described previously. Once all variables have been converted to electrical quantities a computor can provide an estimate of both bending strength and stiffness.

Data presented herein demonstrate the possibilities of the test method for determining mechanical properties in bending. Experimentation reported in the literature (2) attests to its use for measuring modulus of elasticity in compression as well as maximum crushing strength. It is highly probable that the properties of each piece of material, whether it be designed for use in flexure or compression, can be measured and computed in 5 to 10 seconds.

Conclusions

Overdesigned wood structures and the sometimes unfavorable position of wood as a structural material have come about largely as a result of its variability and the lack of methods for close estimation of mechanical properties. The problem points up the need of a non-destructive test that will permit a 100 per cent assay of production and determination of the structural characteristics of each unit. Vibration, a mechanical test conducted at an extremely rapid rate and at an amplitude that precludes damage to the material, offers one of the more promising non-destructive test methods. The data collected by means of a relatively simple scheme of testing demonstrate that the characteristics of clear wood can be estimated to an accuracy heretofore considered unattainable.

The problem of associating static and dynamic properties of wood containing defects still remains. However, the success encountered with clear wood of Sitka spruce is sufficiently encouraging to warrant detailed studies of other species containing different types and combination of defects. Once proven, its application is relatively simple considering the advanced status of electronic sensing and computing devices. The inherent advantages of such a system should do much to improve the competitive status of wood.

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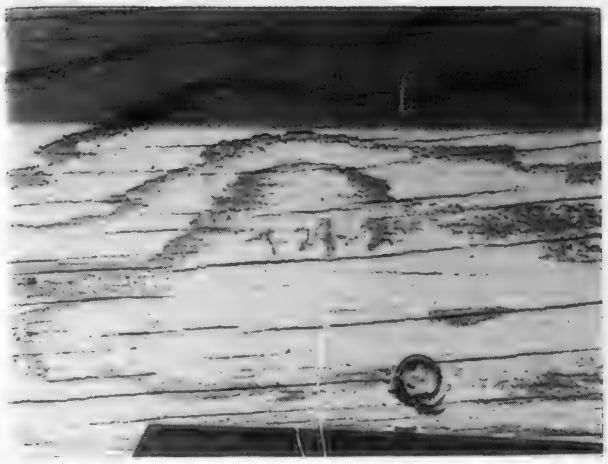


Disintegration of paint by checking and crumbling, after it has served its useful life. Note how the "crumbs" fall from the bands of summerwood long before they come from the springwood underneath. This form of disintegration is characteristic of low-swelling paints.

Disintegration of paint by cracking, curling, and flaking, after it has served its useful life. Note how the "flakes" fall from the bands of summerwood before the springwood begins to be laid bare. This form of disintegration is characteristic of high-swelling paints.

UNDERSTANDING THE MECHANISMS OF

Deterioration of House Paint[1]

F. L. Browne
Forest Products Laboratory[2], Forest Service U. S. Department of Agriculture

Water, especially in conjunction with ultraviolet light, accelerates chemical deterioration. The products of the decomposition cause normal and abnormal failure. Shrinking and swelling caused by water also stress and disrupt paint films.

ALTHOUGH MARKED IMPROVEMENTS have been made in the appearance and some aspects of the wear of house paints, they remain prone to deterioration by undesirable crumbling or flaking from bands of summerwood, especially on such widely available softwoods as Douglas-fir and southern yellow pine; and, under some conditions of service, to unexpectedly early failures by blistering or other abnormalities. For some time the Forest Products Laboratory has therefore been conducting research on the mechanisms of paint deterioration by more fundamental methods than the predominantly empirical procedures that have been customary in the past.

Chemical Changes During Drying and Deterioration

The chemical processes by which paint coatings deteriorate are continuations of much the same oxidative processes by which the coatings are formed in the first place. When paint is exposed to air in a thin film, oxygen reacts at the unsaturated carbon atoms of the drying oil to form hydroperoxides.

--The *Author:* F. L. Browne holds a PhD in colloid chemistry from the University of Wisconsin. He joined the FPL in 1918, and since has been a frequent contributor to the *Journal*.

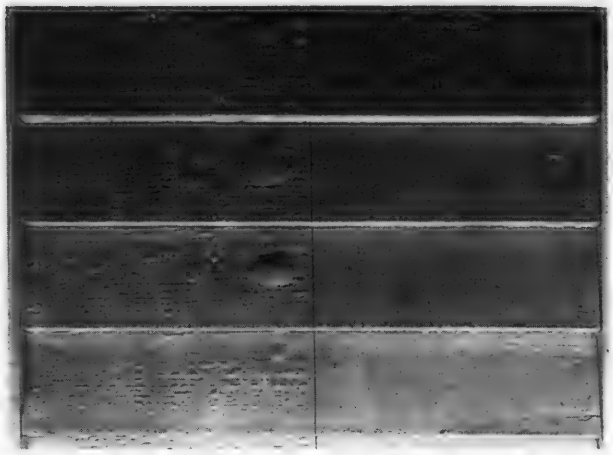
The hydroperoxides initiate chain reactions of two kinds (20, 24, 26, 30, 35)[3]. One kind leads to cross-linked polymers or gels that make the hardened paint film. The other kind proceeds in the opposite direction to split molecules of drying oil and subsequently of the polymerized gel into a succession of smaller oxygenated fragments.

The ultimate products of the disruptive oxidation, which begin to appear even during the initial drying of coatings, are gases or vapors that escape from the film, such as water, carbon dioxide, carbon monoxide, formaldehyde, and formic acid (20, 21, 24, 25, 26). Intermediate products are larger fragments that are less volatile or nonvolatile. They include propionic, caproic, nonylic, and azelaic acids, still higher saturated and unsaturated acids (22, 39), hydroxyacids (33, 38), aldehydes (2), ketones (20, 22, 24, 26), and glycerol (39), although the ester linkage to the glycerol is stable enough to persist through aging and weathering (22). The nonvolatile fragments remain in the film until it comes in contact with water, when those that are soluble in water may be extracted. The insoluble oxidation products and the oxygenated groups formed in the polymerized gel are highly polar and hydrophilic, and therefore increase the capacity of the film for absorbing water (22, 24, 49).

Pigments materially alter the course of both polymeric and disruptive oxidation and therefore the drying and deterioration of coatings. The consumption of oxygen and the evolution of volatile products are increased by some pigments and decreased by others (41). Such effects are exerted by pigments that are as inert chemically as titanium dioxide, silica, and barium sulfate as well as by chemically active pigments. Basic pigments, such as zinc oxide and white lead, in addition react with acid decomposition products to

[1] Presented at the Short Course in Paint Technology at the Univ. of Florida, Gainesville, Feb. 1959.
[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.
[3] Numbers in parentheses refer to Literature Cited at the end of this report.

Abnormal disintegration of paint by alligatoring. In this case a pigment house paint was applied over a clear varnish used as a wood sealer in place of a paint primer.



The boards on the left were painted with three coats of a high-swelling, titanium-lead-zinc paint, which blistered badly under conditions of cold-weather condensation. Boards on the right were primed with low-swelling aluminum house paint and finished with two coats of the same titanium-lead-zinc paint.

form soaps that may be more or less soluble in water than the corresponding free acids (33, 38, 39).

The nonvolatile decomposition products that remain in the film significantly affect the properties of coatings (32, 45, 49). Liquids or soft solids of low molecular weight act as plasticizers to impart flexibility and distensibility and perhaps to ketp the degree of cross linking of the polymeric gel from becoming excessive. Loss of the plasticizing products by leaching with water impairs flexibility and distensibility and promotes embrittlement. On the other hand, hard, crystalline solids, such as are formed by some of the zinc soaps, act like pigments to make the film harder and less flexible. Water-soluble or strongly hydrophilic decomposition products make the film absorb more water. Although the absorbed water acts helpfully to plasticize the film, it also has the harmful effect of causing swelling.

In the first stages of drying, there is a gain in weight despite loss of volatile products, because the weight of oxygen retained in the film exceeds the weight of volatile products lost (18). The oxygen retained soon reaches a maximum. Linseed oil, for example, contains 11.5 percent of oxygen to begin with, but may gain more than 13 percent to reach a maximum of 25 percent. But loss of volatile products continues during aging or weathering, so that the weight of the film declines from its maximum. The volume of the film, on the other hand, begins to shrink from a very early stage in the drying (19), partly from loss of volatile products and partly from increase in density of the oxidized film. Thus the density of linseed oil increases from 0.93 to more than 1.1 within 2 days.

Young coatings that are highly plasticized by oxidation products and by incomplete cross linking of the polymeric gel can adjust their internal stresses. Old coatings that are more completely cross linked and have lost plasticizers necessarily develop great internal stresses (1, 35, 36, 46), because two of their three dimensions must continue to conform to the requirements of their substrate. This leaves only the thickness free to take up the changes in volume. Further changes in volume imposed by periodic absorption of water and redrying during weathering eventually build up enough internal stress to disrupt the coating.

Light speeds both the polymeric and the disruptive oxidation in the drying and deterioration of coatings (20, 21, 25, 26). Light is more effective the shorter its wave length (24, 35, 42). The ultraviolet components of sunlight with wave lengths from 280 to 400 millimicrons are more effective than visible light with wave lengths from 400 to 800 millimicrons. Wave lengths shorter than 280 millimicrons, although still more effective, are of little practical importance because they are absorbed in the atmosphere before sunlight reaches the earth's surface. Window glass absorbs much of the ultraviolet from sunlight.

On the other hand, the longer waves of light penetrate to the full depth of paint films of ordinary thickness, whereas the shorter ultraviolet light penetrates only part way (25). Pigments of high opacity to ultraviolet light, such as zinc oxide (40), further restrict the action of short waves to a very thin superficial layer. The shorter waves stimulate particularly the production of volatile compounds of carbon, and result in deterioration by chalking and erosion whereas longer waves promote less drastic cleavage with volatilization of more hydrogen (as water) than carbon, increased cross linking, and further shrinking and embrittlement of the coating (25, 26, 37).

Less attention has been paid to the action of water in deterioration, although its importance has been recognized (26, 35, 42, 50). It has even been claimed that water causes much the same deterioration as light, but at a slower rate (43, 45). Certainly paints exposed outdoors are repeatedly brought in contact with water (28), which, from the knowledge already reviewed, can be expected to affect materially the composition and properties of the coating and contribute to faster deterioration outdoors than indoors.

Experimental Procedure

Previous publications reported the behavior of paint coatings and free films (detached from their substrate), both before and after weathering, when brought in contact with water (4 to 14). The absorption of water, changes in density, volumetric swelling, changes in dimensions, recovery on redrying, extraction of water-soluble ingredients, and losses by volatilization and leaching during weathering were measured. The coatings were weathered by exposure either outdoors or in a Weatherometer so that deterioration was accomplished by the combined action of sunlight and water, together with oxygen. Changes during the first 10 days after the liquid paints were applied, that is while the paints dried and hardened, were not measured.

The experiments described here afford information about changes in

weight, volume, and density of some linseed oil paints during the drying period and about the effects on these properties of subsequent exposure under various conditions for 15 days and their behavior toward water. In particular, the purpose was to learn more about the relative action of water and light in paint deterioration.

All of the 8 paints used were made at 30 percent pigment volume in a vehicle of raw linseed oil containing lead-manganese naphthenate drier. The composition was always 0.261 gallon of pigment, 0.609 gallon of linseed oil, and 0.130 gallon of mineral spirits and liquid drier to the gallon of paint. The paints differed only in pigment composition. In paint *L* the pigment was entirely basic carbonate white lead, in paint *Z* lead-free zinc oxide, in paint *T* rutile titanium dioxide, in paint *A* antimony oxide, in paint *X* magnesium silicate. The other 3 paints contained mixtures of 3 or 4 of these pigments from the same lots. In paint *TLX* the pigment consisted of 14 percent titanium dioxide, 40 percent white lead, and 46 percent magnesium silicate by volume. In paint *TZX* the pigment contained 19 percent titanium dioxide, 20 percent zinc oxide, and 61 percent magnesium silicate. In paint *TLZX*, the pigment contained 14 percent titanium dioxide, 20 percent white lead, 20 percent zinc oxide, and 46 percent magnesium silicate.

The paints were spread on clean tinplate by means of a suction plate and doctor blade, at a thickness of coating calculated to yield 4 mils after the volatile thinner evaporated. The weight of paint was determined by weighing each tinplate before and immediately after application. The initial weight, volume, and density of the coatings after evaporation of the volatile thinner were calculated from the composition of the paint, the bulking values of the ingredients, and the weight of paint applied. The coated tinplates were allowed to stand 10 days in light filtered through a glass window facing north. Temperature and humidity were not controlled, but the temperature did not depart much from 80°F. and the relative humidity was always less than 40 percent. Specimens of each paint were weighed daily for the first 10 days and then at suitable intervals up to 83 days to follow the changes in weight.

On the 10th day, a set of specimens, one for each paint, was selected and the coatings stripped from the tinplates by floating them on mercury until the tin was amalgamated and the paint film left free. The free films were submitted once to test for their behavior toward water by the methods described in previous publications (9).

Table 1.--Changes in weight, volume, and density of paint coatings while drying and aging indoors in dry air[1].

Paint[2]	Density			Changes in weight				Loss in volume after	
	1st day	10th day	25th day	Age at maximum weight	Maximum gain	Decline from maximum after 10 days	Decline from maximum after 25 days	Decline from maximum after 83 days	10 days	25 days
				Days	Gm./cm.³	Gm./cm.³	Gm./cm.³	Gm./cm.³	Mm.³/cm.³	Mm.³/cm.³
L (white lead)	2.70	2.90	2.94	6	6.75	0.50	1.13	3.18	47.7	63.0
Z (zinc oxide)	2.32	2.47	2.52	8	9.18	.46	.63	1.79	[illegible]	[illegible]
T (titanium dioxide)	1.91	2.04	2.10	2	10.75	1.29	2.56	[illegible]	17.1	[illegible]
A (antimony oxide)	2.38	2.53	2.54	2	12.25	1.76	3.02	5.00	14.9	[illegible]
X (magnesium silicate)	1.51	1.68	1.69	6	7.90	.55	1.70	[illegible]	59.1	68.
TLX (titanium-lead-silicate)	2.04	2.23	2.24	6	7.63	.38	.80	2.68	51.3	54.0
TZX (titanium-zinc-silicate)	1.74	1.92	1.92	8	9.72	[illegible]	.68	2.56	[illegible]	[illegible]
TLZX (titanium-lead-zinc-silicate)	1.97	2.15	2.14	8	8.50	.17	.20	1.89	[illegible]	[illegible]

[1] Coatings on tinplate were approximately 4 mils thick when 10 days old. Changes calculated for 1 cubic centimeter of liquid paint free from volatile thinner.

[2] Linseed oil paint at 30 percent pigment volume.

Also on the 10th day, 6 other sets of specimens were taken, each set to be submitted for 15 days to one of the following conditions of exposure:

1. *Indoor light, dry air:* This was a continuation of the conditions already described for the initial 10-day drying period.

2. *Darkness, dry air:* The specimens were kept in a totally dark room in which temperature and relative humidity were the same as in condition 1.

3. *Darkness, damp air:* The specimens were kept in a totally dark room held constantly at 80° F. and 97 percent relative humidity.

4. *Repeated water:* From 7 to 10 a.m. and again from 2 to 5 p.m. daily the specimens were submerged in rapidly running tap water at about 50° F. Between immersions, the specimens were allowed to drain and dry under condition 1.

5. *Sunlight without water:* The specimens were irradiated constantly with artificial sunlight from a flaming carbon arc enclosed in a Corex D glass globe.

6. *Sunlight with water:* The specimens were irradiated constantly with the artificial sunlight and sprayed generously with distilled water for approximately 2 minutes in each period of 20 minutes.

Tests under conditions 5 and 6 were conducted simultaneously in a Weatherometer with the specimens to be kept dry arranged in the upper tier of the rotating drum and protected by suitable baffles from the water sprayed on the specimens of the lower tier at each rotation of the drum.

At the end of the 15-day exposure periods, when the specimens were 25 days old, the exposures were discontinued, the specimens were allowed to dry, were weighed, and the films stripped from the tinplate for test for behavior toward water.

Aging Indoors in Dry Air

Within 24 hours after application, all paints were gaining in weight. Evidently most of the volatile thinner had evaporated, a minimum in weight had been passed, and absorption of oxygen was greater than the combined losses of volatile decomposition products and any residue of volatile thinner still left. With further passage of time, all paints reached a maximum weight and then declined when losses of volatile products began to exceed further absorption of oxygen.

The changes in weight, volume, and density of the 8 paints during drying and aging indoors in dry air are summarized in Table 1. It is to be remembered that, in Table 1, the changes are computed from the starting point of the weight, volume, and density of the unoxidized paint free from volatile thinner, and that all paints contained the same volumetric proportion of linseed oil at the outset.

All paints reached maximum weight within the 10-day drying period, but they differed strikingly in the magnitude of the maximum and in the time required to reach it. Paints *A* and *T* in 2 days reached maxima of 12.25 and 10.75 centigrams per cubic centimeter; *L*, *X*, and *TLX* took 6 days to reach maxima of 6.75 to 7.90, and paints *Z*, *TZX*, and *TLZX* required 8 days to reach 8.50 to 9.18. After they passed the maximum, paints *A* and *T* declined in weight more rapidly than the other paints, and the 3 paints that contained zinc oxide declined less rapidly than the others. Although all of the paints still exhibited a net gain in weight even after 240 days, all experienced a substantial loss in volume with consequent increase in density within the first 10 days. There usually was further loss in volume and increase

Table 2.--Behavior of 10-day-old paint films during soaking and after redrying.[1]

Paint[2]	Change during soaking					Soluble material extracted	Change after redrying			
	Density	Water absorbed	Volume	Area	Thickness		Density	Volume	Area	Thickness
		Cg/cm³	Percent	Percent	Percent	Cg/cm³		Percent	Percent	Percent
L (white lead)	-0.07	5.6	+5.9	+1.0	+2.4	3.4	+0.04	-2.6	-0.2	-2.4
Z (zinc oxide)	-.69	91.0	+90.5	+33.4	+41.0	3.3	+.02	-2.3	+8.9	-10.4
T (titanium dioxide)	-.15	22.3	+22.6	+10.0	+ 8.8	2.9	+.04	-2.9	+1.0	-3.9
A (antimony oxide)	-.03	1.8	+2.2	+.5	+.5	1.3	+.01	-1.2	-.5	-.7
X (magnesium silicate)	-.20	42.8	+43.7	+15.0	+22.2	3.1	+.02	-3.1	+1.9	-4.8
TLX (titanium-lead-silicate)	-.15	14.5	+14.9	+4.5	+7.7	3.5	+.02	-2.5	-.1	-2.3
TZX (titanium-zinc-silicate)	-.38	71.9	+72.0	+33.5	+27.1	3.1	+.008	-2.0	+9.5	-10.7
TLZX (titanium-lead-zinc-silicate)	-.39	50.6	+50.7	+17.3	+27.0	2.6	+.005	-1.4	+4.1	-5.5

[1] Soaked in distilled water for 3 days and then allowed to dry out for 3 days in a desiccator. Coatings, approximately 4 mils thick, stripped from their substrate before starting the soaking test. Percent change calculated on the basis of the volume of the dried film before soaking in water.

[2] Linseed oil at 30 percent pigment volume.

in density during the next 15 days except for paint *TLZX*, which apparently recovered a small part of its initial loss in volume with a slight decrease in density.

Table 1 shows clearly that none of the pigments used can be considered "chemically inert." All exert profound effects on the course of oxidation of the drying oil. In particular they affect the extent of disruptive oxidation, which produces volatile products that escape from the coating and presumably also somewhat larger fragments that remain behind but are extractable by solvents (36). Pigments likewise affect the shrinkage in volume during drying and aging. Still further effects of pigments on the behavior of paint films toward water are therefore to be expected.

When 10-day-old coatings were stripped from their substrates and the free films soaked in distilled water for 3 days and then allowed to dry again for 3 days in a desiccator, they behaved as reported in Table 2. The changes are computed on the basis of the volume of the 10-day-old films rather than that of the volume of nonvolatile in the liquid paint as in Table 1. All films absorbed water and swelled in volume but in widely differing amounts. Paint *A* absorbed only 1.8 centigrams per cubic centimeter, whereas paint *Z* absorbed 91.0 centigrams. Volumetric swelling was nearly but not necessarily exactly equal to the volume of water absorbed. Film density decreased in proportion as the absorption increased.

When redried, all films were lighter in weight than they were immediately before soaking by the weight of soluble matter extracted by the water. Most of the soluble material can be recovered by evaporating the soaking water to dryness (8). From the data of Table 1 it can be shown that loss of volatile material during the 3 days in the desiccator in no case was as much as 0.2 centigram per cubic centimeter. The redried films shrank below their volume before soaking by amounts that were comparable to the solubility losses. The density of the redried films was greater than it was before soaking.

The free films swelled in volume when soaked in water by increasing both in area and in thickness. The paints differed widely in the distribution of their volumetric swelling between swelling in area and swelling in thickness. Thus paint *Z* increased 33.4 percent in area and 41.0 percent in thickness, whereas paint *TZX* increased 33.5 percent in area but only 27.1 percent in thickness. Shrinkage on redrying was always accomplished more by contraction in thickness than in area; in fact, the redried films of 5 of the paints remained larger in area although much thinner than they were before soaking. The paints containing zinc oxide, which are harder and less flexible than the others, contracted least in area when redried.

Deterioration under Different Conditions of Exposure

Changes in weight, volume, and density of the paint coatings under the 6 different conditions of exposure already described are reported in Table 3. Table 3 gives also the behavior of free paint films after exposure when submitted to the soaking water test.

During 15-day exposure in dry air with or without indoor light (conditions 1 and 2), the changes in weight, volume, and density were small, as was to be expected in the relatively brief exposure period. Much longer exposure and closer control of the exposure conditions would be needed for satisfactory quantitative measurements to reveal any effect of indoor light on the rates of deterioration. Nevertheless, measurable deterioration clearly occurred both in indoor light and in darkness, as is indicated by loss in weight usually accompanied by loss in volume and gain in density. Paint *TLZX*, however, increased slightly in volume and decreased slightly in density despite its loss in weight, and paint *TZX* likewise decreased in density. Table 1 shows that these 2 paints declined from their maximum weight less rapidly than the other paints up to the 25th day, but thereafter they lost weight about as fast as the others. The behavior of the free films toward water after the 15-day exposure in dry air with and without indoor illumination did not differ greatly from the behavior of the 10-day-old films reported in Table 2.

Exposure to damp air in darkness for 15 days, condition 3, markedly altered the behavior of the free films toward water by increasing the absorption of water and swelling. Thus paint *L*, which swelled 5.9 percent in water after exposure to dry air in darkness, swelled 11.5 percent after exposure in damp air. Paint *Z* swelled 91.5 percent and 121.5 percent in water after exposure to dry and to damp air, respectively. The effect of damp air on weight, volume, and density does not appear to be consistent. Its effect may be complicated by chemical reactions of moisture with decomposition products formed in the presence of some pigments but not in the presence of others. Thus paint *Z*, which in previous tests (6) was found to absorb 20 centigrams of moisture per cubic centimeter in 7 days in 97 percent relative humidity, showed (Table 3) an anomalous gain after redrying of 1.4 centigrams per cubic centimeter whereas paint *L*, which in the previous tests absorbed only 2.9 centigrams of moisture per cubic centimeter, exhibited greater loss in weight and volume in damp than in dry air. Similar differences between paints *Z* and *L* have been reported by others (40). On the whole, the data of Table 3 support the conclusion that dampness is more potent than indoor light in altering the properties of paint coatings, at least in the early stages of deterioration.

Repeated immersion of the paint coatings in water, condition 4, produced greater losses in weight and in volume, usually with greater increase in density, than any of the other conditions of exposure without sunlight. These greater losses were due in part but perhaps only in part, to extraction of soluble materials by the water, because the free films nearly always exhibited a diminished content of water-soluble substances when they were tested after the exposure period. In the test of the free films for behavior toward water after exposure, the films exposed to repeated immersion in water always swelled much more than

hose exposed to dry air with or without indoor light, but they swelled omewhat less than those exposed to amp air. This effect was probably aused by the water-soluble products xtracted during the repeated immeron treatments.

Exposure to artificial sunlight without water in the Weatherometer (condition 5), produced much greater loss weight, loss in volume, and increase density than did any of the exposure onditions without sunlight. But water cting in conjunction with sunlight condition 6), caused still further hanges that were often as great as hose produced by sunlight alone. Thus or paint *T* sunlight alone increased he weight loss from 1.1 centigram per cubic centimeter in dry air and darkness to 7.2 centigrams, whereas water with sunlight increased the weight loss to 21.9 centigrams. In practice, water may be even more important than the data indicate, because the test conditions were such that each exposure to water was very brief, 2 minutes of spray, possibly 5 or 6 minutes to drain and dry, followed by 12 or 13 minutes of dryness and warmth. Water could scarcely penetrate the coatings very deeply. In natural weathering the periods of wetness, although less frequent, usually last long enough to permit thorough penetration of the coatings (28).

The 3 paints that contained zinc oxide (*Z*, *TZX*, and *TLZX*) suffered smaller losses of weight and of volume during exposure to sunshine, either with or without water, than any of the other paints. On the other hand, the losses were greater for the magnesium silicate paint *X* than for any of the others. Zinc oxide is highly absorptive of ultraviolet light, whereas magnesium silicate is more transparent than any of the other pigments to both ultraviolet and visible light (40).

After exposure to sunlight, free films of paints *L* and *A* absorbed more water in the soaking test than they did before exposure (Table 2) or after exposure to dry air in darkness. These are paints of exceptionally low absorption; in fact, they absorb less water than films of unpigmented linseed oil (9, 11). After exposure to sunlight alone, the swelling in water was nearly as much percentagewise as the absorption of water but after exposure to water and sunlight together the swelling lagged behind the absorption. This is attributed to development of porosity within the paint coating when water extracts soluble matter after the coating has become rigid enough to resist collapse.

Table 3.--Effect of conditions of exposure on the changes in paint coatings and on the behavior of their free films during soaking and after redrying[1].

Exposure conditions[2]	Change during exposure[2]			Change during soaking[3]				Change on drying[5]	
	Density	Weight	Volume	Density	Water absorbed	Volume	Soluble material extracted	Density	Volume
		Gr. per cm.[3]	Percent		Gr. per cm.[3]	Percent	Gr. per cm.[3]		Percent
PAINT L (white lead)									
Indoor light, dry air	+0.038	-0.7	-1.6	-0.076	+6.5	+6.6	2.6	+0.050	-1.4
Darkness, dry air	+.033	-.7	-1.5	-.067	+5.8	+5.9	2.6	+.040	-1.4
Darkness, damp air	+.040	-.9	-1.8	-.182	+11.5	+11.7	1.9	+.050	-1.4
Repeated water	+.061	-2.7	-3.0	-.199	+7.4	+7.6	1.1	+.064	-1.4
Sunlight without water	+.260	-10.6	-11.6	-.168	+10.7	+9.6	4.1	+.244	-1.4
Sunlight with water	+.356	-17.3	-16.3	-.116	+6.8	+6.9	1.3	-.099	+1.0
PAINT Z (zinc oxide)									
Indoor light, dry air	+0.057	-0.2	-2.3	-0.752	+98.5	+98.0	1.8	+0.015	-1.8
Darkness, dry air	+.053	-.3	-2.1	-.720	+92.0	+91.5	2.9	+.014	-1.7
Darkness, damp air	+.041	+1.4	-1.2	-.822	+122.0	+121.5	3.0	+.025	-2.2
Repeated water	+.057	-1.4	-3.0	-.782	+105.0	+104.0	1.1	+.010	-1.1
Sunlight without water	+.194	-6.0	-9.2	-.416	+35.2	+34.4	1.5	+.008	-.9
Sunlight with water	+.259	-11.2	-13.5	-.392	+31.2	+30.4	.9	+.009	-.7
PAINT T (titanium dioxide)									
Indoor light, dry air	+0.054	-1.3	-3.5	-0.261	+34.2	+34.5	4.2	+0.044	-4.2
Darkness, dry air	+.045	-1.1	-2.5	-.263	+35.4	+35.5	4.7	+.045	-4.3
Darkness, damp air	+.057	+.1	-3.6	-.365	+52.7	+52.7	4.5	+.041	-3.6
Repeated water	+.078	-2.8	-5.5	-.303	+39.2	+39.2	3.1	+.027	-3.1
Sunlight without water	+.134	-7.2	-9.5	-.062	+9.6	+9.8	5.4	+.054	-4.8
Sunlight with water	+.332	-21.9	-23.0	-.091	+8.3	+8.6	1.3	+.023	-1.5
PAINT A (antimony oxide)									
Indoor light, dry air	+0.010	-1.3	-1.0	-0.001	+1.3	+1.6	2.2	+0.027	-1.9
Darkness, dry air	+.001	-1.3	-.5	-.001	+1.3	+1.3	2.1	+.019	-1.6
Darkness, damp air	-.014	-.6	+.5	0	+2.0	+2.1	2.4	+.028	-2.0
Repeated water	+.024	-2.9	-2.1	-.010	+1.3	+1.5	1.5	+.017	-1.3
Sunlight without water	+.197	-8.1	-10.3	+.024	+3.3	+3.1	6.0	+.079	-5.0
Sunlight with water	+.457	-22.1	-22.7	-.010	+2.2	+1.9	2.5	+.026	-1.7
PAINT X (magnesium silicate)									
Indoor light, dry air	+0.005	-1.2	-1.0	-0.167	+34.0	+34.1	5.2	+0.019	-4.2
Darkness, dry air	+.008	-.6	-.7	-.193	+40.5	+40.7	5.4	+.021	-4.4
Darkness, damp air	-.019	-1.2	+.3	-.358	+99.0	+99.3	5.8	-.051	-.4
Repeated water	+.009	-4.4	-3.0	-.250	+57.8	+57.8	3.7	+.010	-2.8
Sunlight without water	+.166	-14.7	-17.0	-.206	+38.4	+38.3	14.0	+.066	-10.8
Sunlight with water	+.299	-27.4	-29.2	-.047	+ 4.9	+ 5.2	1.7	+.006	-1.1
PAINT TLX (titanium dioxide, white lead, magnesium silicate)									
Indoor light, dry air	+0.005	-.4	-.3	-0.115	+12.0	+12.3	3.3	+0.030	-2.8
Darkness, dry air	0	-.1	-.1	-.110	+11.4	+12.0	3.4	+.025	-3.0
Darkness, damp air	-.017	-.5	+.6	-.158	+15.8	+16.1	1.5	+.016	-1.4
Repeated water	+.020	-3.0	-2.1	-.139	+13.4	+13.6	1.8	+.018	-1.5
Sunlight without water	+.179	-9.4	-11.5	-.126	+11.3	+11.2	2.9	+.031	-2.5
Sunlight with water	+.241	-16.1	-16.3	-.102	+8.1	+8.3	2.4	+.014	-1.5
PAINT TZX (titanium dioxide, zinc oxide, magnesium silicate)									
Indoor light, dry air	-0.004	-0.4	-0.2	-0.371	+68.0	+68.2	3.8	+0.019	-2.9
Darkness, dry air	-.007	-.2	0	-.360	+65.7	+66.0	3.5	+.023	-3.0
Darkness, damp air	-.019	-.2	+.7	-.438	+94.6	+94.9	2.9	+.019	-2.5
Repeated water	-.011	-1.0	-.3	-.377	+70.5	+70.8	2.9	+.011	-2.0
Sunlight without water	+.071	-5.0	-5.4	-.244	+33.7	+33.3	2.0	+.014	-1.2
Sunlight with water	+.091	-5.4	-5.1	-.298	+42.2	+42.3	1.2	+.007	-.9
PAINT TLZX (titanium dioxide, white lead, zinc oxide, magnesium silicate)									
Indoor light, dry air	-0.009	-0.4	+.4	-0.299	+36.3	+36.6	3.2	+0.018	-2.3
Darkness, dry air	-.008	-.2	+.4	-.335	+42.3	+42.7	3.3	+.022	-2.5
Darkness, damp air	-.014	-.3	+.5	-.472	+72.2	+72.5	3.0	+.024	-2.5
Repeated water	-.010	-1.3	0	-.358	+46.2	+46.6	2.8	+.018	-2.1
Sunlight without water	+.087	-4.4	-6.0	-.250	+26.5	+25.5	2.2	-.007	-.7
Sunlight with water	+.119	-7.4	-8.5	-.289	+29.4	+29.2	1.5	-.006	-.4

1 Coatings on tinplate dried indoors for 10 days (approximately 4 mils thick when dry), then exposed to the conditions indicated, after which they were stripped from the tinplate and tested for behavior toward water.

2 From eleventh to twenty-fifth day inclusive.

3 Based on volume of film on tenth day.

4 Based on volume of film on twenty-fifth day. Soaking time 3 days.

5 Based on volume of film on twenth-fifth day. Dried 3 days in desiccator after soaking.

All of the other paints, after exposure to sunlight with or without water, absorbed less water and swelled less than they did before exposure or after exposure to dry air in darkness. The difference was especially striking for those paints that were highest in swelling before exposure, namely, the 3 paints that contained zinc oxide. The zinc-containing paints differed from all the others also in that the absorption of water and swelling after exposure to water and sunlight together were nearly as great or even greater than they were after exposure to sunlight alone. The other paints were less absorptive and swelled less after exposure to water and sunlight than after exposure to sunlight alone.

Paint films after exposure to water and sunlight always yielded less soluble material to the soaking water than corresponding films after exposure to sunlight alone and also less soluble matter than films, with the unexplained exception of paint *A*, before exposure or after exposure to dry air in darkness. On the other hand, films of paints containing no zinc oxide, with the unexplained exception of paint *TLX*, yielded more soluble material to the soaking water than the corresponding films before exposure or after exposure to any of the other conditions. Paint *X* after exposure to sunlight alone yielded the remarkable amount of 14.0 centigrams of soluble material per cubic centimeter. The 3

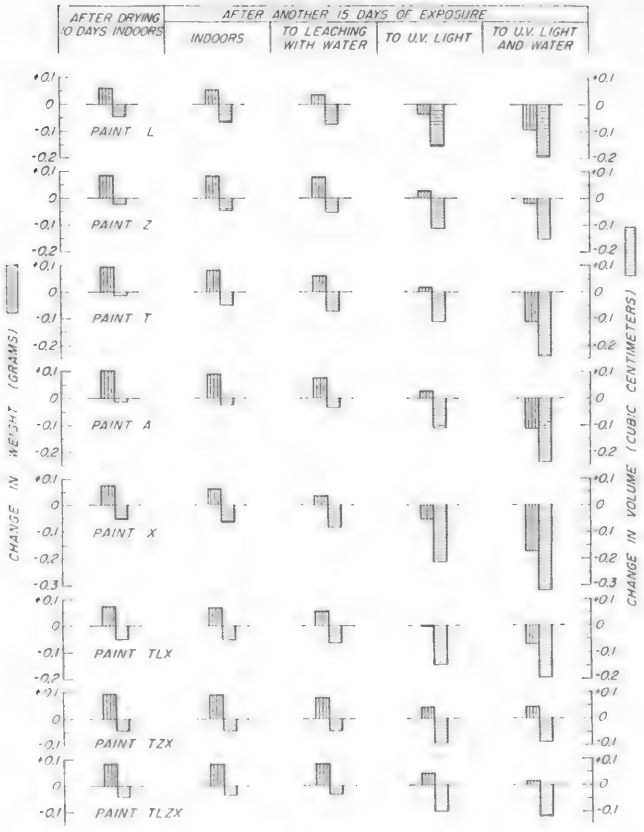


Fig. 1.—Changes in weight and in volume of films under various conditions of exposure. Films contained 1 cubic centimeter of non-volatile when applied.

zinc-containing paints after exposure to sunlight alone gave up less soluble material than their films before exposure or after exposure to dry air in darkness. Apparently sunlight, but not indoor light, acts to increase the formation of soluble decomposition products that remain in the coating unless extracted by water. Zinc oxide, because of its high absorption of ultraviolet light, shields nearly all but the outer surface of the coating from such action. The low opacity of magnesium silicate, on the other hand, offers even less shelding than the other pigments studied.

The changes in weight, volume, and density recorded in Table 3 are those that occurred during the 15-day exposure periods, calculated on the basis of the volume of the dry coatings when 10 days old. Fig. 1 is a graphic presentation of the changes in weight and volume that occurred, first during the 10-day drying period, and then during the entire 25 days for drying and exposure to each test condition, omitting the two exposures in darkness. The changes are calculated on the basis of the volume of unoxidized paint free from volatile thinner applied to begin with. After drying for 10 days, the coatings still retained a net gain in weight, the magnitude of which varied with the kind of pigment in the paint. There was, however, already a loss in volume.

During the succeeding 15 days of exposure, both weight and volume decreased, but to differing extents according to the conditions of exposure and the kind of pigment present. The decreases were least rapid for exposure to dry air indoors, were distinctly faster for repeated immersion in water, still faster for exposure to sunlight, and fastest for exposure to sunlight and water together. Among the 8 paints, the decline in weight and volume when exposed to sunlight was slowest for the 3 paints that contained zinc oxide, but no explanation appears for the greater decline in the paint with 100 percent than in the paints with only 20 percent of zinc oxide. The magnesium silicate paint lost weight and volume faster than any of the other paints.

Significance of the Experiments

The import of the experiments is that deterioration proceeds in much the same way under all conditions of exposure in which oxygen is present, but that the rate of deterioration can be speeded greatly by such conditions as exposure to sunlight and exposure to water. In darkness or in indoor light, water in the form of either vapor or liquid makes paint films more sensitive to absorption of water and swelling, and in the liquid form it accelerates loss of weight and volume by extracting soluble decomposition products. Indoor light has little stimulating effect on deterioration.

Sunlight, which contains ultraviolet wave lengths, accelerates formation of decomposition products, both volatile products that escape at once and soluble products that remain in the film unless extracted by water. No doubt sunlight also increases polymeric oxidation and cross linking of the gel structure, because it makes coatings more resistant to absorption of water and swelling—except, of course, those coatings that are highly resistant before exposure. When water acts together with sunlgiht, deterioration attains it greatest speed, not only because the soluble decomposition products are extracted but because volatile products form and escape more rapidly. Pigments of high absorption for ultraviolet light, however, retard the action of sunlight, presumably by keeping the ultraviolet light from penetrating much beyond the exposed surface.

Coatings of house paint are called upon to accommodate themselves to substantial changes in volume from two sources, 1) the continual loss in volume from deterioration of the coating, and 2) repeated absorption of water with swelling, redrying with shrinkage, and extraction of soluble components by water. To maintain adhesion to the substrate and remain unbroken, the coatings must make the adjustments entirely by changes in thickness, except as accompanying movement of the substrate may permit some change in area.

The soaking tests reveal that free films, unrestrained by substrates, distribute any change in volume among all three dimensions. Attachment to a substrate, therefore, imposes restraint that necessarily distorts the internal structure. Only a liquid free to flow can submit to such restraint without developing internal stress. As a coating dries and acquires rigidity, internal stresses come into play that increase in magnitude as the rigidity increases. Very young coatings can relax the stresses largely by plastic deformation (23, 32). Older coatings that remain sufficiently distensible can withstand the stresses by elastic deformation. But such adjustments become increasingly difficult as further weathering increases the rigidity of the coating and deprives it of the simpler compounds that act as plasticizers. Eventually the internal stresses exceed the cohesion of the coating or its adhesion to the substrate, whereupon the coating breaks and begins to come loose.

Disruptive stresses in coatings on wood have often been attributed to

movement of the wood surface with change in moisture content (29) Perhaps there are circumstances under which this can occur, but the disintegration of house paints under normal conditions of service cannot be explained in that way (15).

Applications to Normal House Paint Behavior

Although present knowledge of the mechanisms of paint deterioration is far from complete, an attempt to apply to the behavior of paints as commonly observed on houses and test fences may suggest directions for promising further research. The Forest Products Laboratory recognizes six stages in the normal wear of house paints: the soiling, flatting, chalking, fissure, disintegration, and advanced break-up stages (27).

The Soiling Stage: Newly applied paint gradually becomes dirty. Carbonaceous dirts cling to paint more firmly than do siliceous dirts, glossy paints soil more seriously than otherwise similar flat paints, and the presence of moisture greatly facilitates the attachment of dirt (31, 44). Apparently dirts that are wet by oil more readily than by water stick to the oil vehicle still present in generous amount in the surface of young glossy paint. The actions of water to swell, soften, render the oily surface more tacky, and displace cushions of absorbed air may bring paint and dirt into closer contact. The joining of paint and dirt particles by a film of water, and the subsequent evaporation of the water at the periphery of the junctions, will draw dirt and paint together by the force of surface tension. The water-soluble substances extracted from paint by water may play a part, and conceivably account for the fact that some paints gather less dirt than do other paints that differ only in kind of pigments.

Growth of fungi on paint, commonly called mildew, occurs only when there is moisture, because the microorganisms require water for their metabolism. The organic material extracted from paint by water may provide food for the fungi. Zinc oxide in paint is strongly inhibitive to fungi. Its effect is clearly due to the toxicity of soluble zinc soaps, because zinc has been found in generous amounts in the aqueous extracts from paints containing zinc oxide (4, 8). Soluble salts of lead are also poisonous to fungi, but white lead in paint, although not without prohibitive effect, affords less protection than zinc oxide. The aqueous extracts from paints may contain a little lead (38), but they contain much less lead than zinc (4, 8).

The Flatting Stage: House paints gradually lose their initial gloss and become dull or flat. Losses of volatile products and leaching of soluble products, which proceed most rapidly at the exposed surface, destroy the superficial layer of oil vehicle and lay bare the granular bed of pigments (46). In addition, contraction in volume from deterioration of deeper parts of the coating and distortion from repeated swelling and shrinking contribute to the roughening of the surface until its initial ability to reflect light specularly gives way to markedly diffuse reflection. Flatting occurs exceedingly slowly in dry air indoors. It is hastened by contact with water, by the action of sunlight, and particularly by joint action of sunlight and water in the order indicated by the changes in weight and volume recorded in Fig. 1. The part played by water should not be overlooked. House paints and automotive finishes that dull rapidly in the climate of Florida retain their gloss for a much longer time in the equally sunny but very dry climate of southern Arizona (48).

The Chalking Stage: Continuation of the processes that cause flatting eventually destroys the binding medium by which those particles of pigment near the surface are held in place. When the loose pigment can be rubbed off, the coating is said to be chalking. Chalking is so easily observed that many have been led to attribute to it the gradual erosion by which paint coatings diminish in thickness (16). But the normal service of house paints, unlike that of automotive finishes, affords little opportunity for mechanical removal of chalk by wiping or abrasion. The shrinkage in thickness of coatings of house paint begins long before chalking is evident, and proceeds primarily by decomposition of the vehicle with release of volatile products and extraction of soluble products by water. Mechanical loss of pigment is secondary.

When chalking sets in, some of the dirt previously acquired is usually sloughed off, a process commonly called self-cleaning. The change from an oil-rich glossy composition to a pigment-rich flat composition makes the surface less able to retain dirt. Dirt dislodged by disappearance of the oil to which it was attached is not readily replaced by fresh dirt. The most successful self-cleaning paints nearly always contain zinc oxide, and therefore yield zinc soaps rather than free organic acids to their aqueous extracts (4, 8). It may well be that the zinc soaps have a detergent action that is lacking in the more acidic extracts.

Paints that contain colored pigments fade when they begin to chalk. This has long been recognized as an optical effect of a porous condition of the superficial chalking layer from which oil vehicle has disappeared. Voids left between particles of pigment make highly reflective optical interfaces that restrict penetration of visible light and reduce the extent of selective absorption by the colored pigment. Other evidence of the development of voids in weathered coatings is found in studies of their swelling in water. Before they are weathered, glossy films swell at least as much, sometimes a little more than, the volume of the water absorbed, whereas films weathered sufficiently by exposure to sunlight and water usually swell less than the volume of water absorbed (5, 7, 8, 14). Weathering develops voids that can hold water without adding to the volume of the coating.

It would be highly desirable for house paints to wear entirely away by erosion without any disruption of the coating or loss of adhesion to the substrate. Repainting would then be required when the coating became too thin to continue to hide the substrate, and could be done without troublesome problems with broken and loosened paint. Although such wear by erosion is now obtained with some paints under favorable conditions, no paint can be relied upon to wear that way under all conditions of practical service.

Zinc oxide retards the erosion of paint coatings. On vertical test-fence surfaces facing south at Madison, Wis., Forest Products Laboratory research has shown that linseed oil house paints containing zinc oxide lose about 0.4 to 0.5 mil a year in thickness, whereas paints free from zinc oxide lose nearly 0.7 mil a year (17). These observations are explained in the data of Table 3 and Fig. 1, which show that sunlight is less effective in accelerating the production of both volatile and water-soluble decomposition products when zinc oxide is present than when it is absent.

The Fissure Stage: Young coatings are able to withstand the internal stresses caused by shrinkage in volume and by swelling in water followed by redrying because they can undergo a high degree of both elastic and plastic deformation (23). On aging, such distensibility diminishes at a rate determined by the progress of deterioration under the conditions of exposure (23). Loss by volatilization and leaching of low-molecular decomposition products which have plasticizing action, and increased cross linking of the vehicle gel embrittle the coating (1, 32, 45). The internal stresses from changes in volume become ever greater

until the cohesion of the coating is exceeded. Fissures then occur in the coating to relieve the stresses.

The fractures occur when the coating is dry. Even very brittle coatings are strongly placticized by absorbed moisture, which restores a considerable degree of distensibility (23). Fissures develop more often in dry summer weather than in winter, and are more severe in dry than in damp climates. The following experiment is illustrative. An exceedingly brittle paint composed of titanium dioxide in sodium silicate was applied to matched edge-grain and flat-grain specimens of Douglas-fir and southern yellow pine. The smooth coatings remained intact and unbroken for a long time when kept at reasonably constant relative humidity and temperature. They also remained unchanged when exposed to damp air for 3 days, during which the wood gained 3 percent in moisture content and swelled accordingly. But within an hour after the specimens were restored to lower relative humidity, the coatings cracked severely in a reticulate pattern entirely unrelated to the grain of the wood and long before the wood had lost much of the moisture it had taken up. The cracking clearly originated in stresses within the coating rather than in movement of the wood under the coating.

Fissures may take the form either of checking or of cracking. In checking, the fissures begin in a superficial layer of the coating but may work their way to the bottom of the coating later on. In cracking, the fissures extend at once throughout the depth of the coating. Checking usually occurs, if at all, at an earlier age than cracking. Checking suggests a condition in which a superficial layer of the coating has become embrittled and shrunken at a time when the deeper portions are still distensible and less contracted. Cracking suggests a coating of high strength in tension that has become embrittled throughout before it yields at all. Coatings of white lead paint, which soon develop checking, retain distensibility for a long time even when exposed to sunshine and water, have only moderate strength in tension, and swell very little in water. Paint coatings containing zinc oxide, which imparts cracking tendencies, become embrittled even in the absence of sunlight, have high strength in tension, and become greatly swollen in water. Paints in which early checking relieves internal stresses either may remain free from cracking or, if they do eventually crack, the cracking may occur in a smaller, less conspicous pattern than in paints in which checking is absent and cracking is long delayed.

Coatings applied by brush or doctor blade possess grain that is absent when the coatings are applied by spray gun, especially if the paint contains acicular pigments. The grain comes from orientation of the acicular particles in the last direction in which the paint flows before it hardens. The grain of the paint is revealed in a preferential orientation of cracks in the direction of the last strokes of the brush (23, 32). It appears also in greater swelling across than with the last brush strokes when the films are stripped and soaked in water (4, 8) and in greater strength in tension along than across the grain when the films are tested mechanically (23). The mistaken belief that the direction of cracking is determined by the grain of the wood underneath arises from the fact that paint is customarily applied with the last strokes in the direction of the wood grain.

Checking, which begins in superficial fissures, usually shows little effect of paint grain, develops with random orientation, and rapidly forms an inconspicuous reticulate pattern of fine meshes. The pattern of cracking is usually much coarser and more conspicuous.

The Stage of Disintegration: When checking penetrates to the bottom of the coating, water gains direct access to the wood underneath. Adhesion between coating and wood is greatly weakened by water (34). Moreover, the internal stresses within the coating reach a maximum at the interface between coating and wood, which is the seat of external restraint on the free movement of the coating. There is soon a loosening of the coating along the edges of the checks. The coating then begins to crumble by detachment, one by one, of the tiny polygons outlined by the reticulate fissures.

Paint cracks likewise admit water directly to the wood, and result in loosening along the edges of the cracks. Loose edges of paints that swell greatly in water curl outward markedly, sometimes to the extent of forming scrolls. Free films of such paints curl similarly when soaked in water and even more sharply when redried. The curling may be understood as a response to greater internal stresses in the superficial layer of the coating, where greater exposure has resulted in greater contraction in volume, than in the deeper layers of the coating. Curling tendencies are more marked with high-swelling than with low-swelling paints, but with high-swelling paints the curling can be minimized by formulating the paint as closely as possible to its critical pigment volume.

The loosened areas of coating, now free to change in area as well as in thickness, are often seen to be larger in area than the patch of wood from which they have been detached. This finds explanation in the fact, recorded in Table 2, that high-swelling paints tend to remain distended in area after they have swelled in water and redried. Loose edges of coating eventually break away from the rest of the coating or are broken off by the elements and fall away as flakes.

When disintegration sets in after checking or cracking, the wood begins to affect the course of further deterioration. Loosening occurs much sooner over summerwood than over springwood, particularly so when the bands of summerwood are relatively wide. There is reason to believe that young paint coatings cling to wood by specific adhesion—that is, by a bonding that involves the same polar, oxygenated groups of the vehicle get that are responsible also for cross linking of the gel itself. The progress of weathering may gradually release such wood-paint bonds as the bonds become increasingly engaged in cross linking within the gel, and as plasticizers are lost and the adhesion repeatedly strained by swelling and shrinking of the coating. Specific adhesion may then be lost and the coating left clinging wholly by mechanical adhesion or embedding in the pores of the wood (3). Springwood bands, by reason of their relatively thin-walled wood cells with large cavities, offer much greater play for purely mechanical adhesion than do summerwood bands, which have thick walls and small cavities.

The Stage of Advanced Break-up: The progress of crumbling, flaking, or scaling depends largely on the nature of the wood surface under the paint and only partly on the nature of the paint. As a rule, however, paints that tend to swell little in water and wear by checking and crumbling exhibit slower progress of sloughing from the summerwood and less unkempt appearance in the stage of advanced break-up than paints that wear by cracking in a coarse pattern followed by curling and flaking or scaling.

Applications to Abnormal Paint Behavior

Under some conditions of service, paints depart from their normal pattern of behavior. Among the conditions that lead to abnormal behavior are unsuitable spacing of paint coats or repaintings, unsuitable thickness of coating, incompatibilities between paints, and blistering.

Unsuitable Spacing of Paint Coats or Repaintings: Much experience has shown that oil paints applied while the previous paint was still in the soiling or flatting stage often fail to perform normally. The condition frequently

ccurs when houses are completed late in the fall or winter, are given a priming coat of paint only, and the rest of the painting is deferred for several months until the weather moderates. Such paint jobs seem to be particularly inclined to early failure, often by intercoat peeling or by moisture blistering. The relatively high content of water-soluble substances and greater swelling capacity of young coatings may well be responsible. In addition has been found (12) that paint coatings applied at unsuitably low temperatures contain more water-soluble products and swell more in water than similar coatings applied at higher temperatures.

Much the same explanation may apply to early failures of repaint jobs on parts of a house that, by their position, are sheltered from the full impact of sunshine and rain, such as ceilings of porches and overhanging eaves. It is not unusual for new paint to come loose and scale from older paint or for coatings to become blistered on the well-sheltered areas while the same paint is still performing normally on the fully exposed areas. Absence of the leaching effect of full rainfall, together with longer contact with still water in the form of dew, allows soluble decomposition products to accumulate in the protected coatings to a harmful extent.

Unsuitable Thickness of Coating: Practical experience shows that most good house paints serve best when the coating is between 4 and 5 mils thick. Modern paints will hide satisfactorily at half that thickness, but such thin coatings are more quickly penetrated by water, their content of soluble material is greater, sunlight reaches a greater portion of the film, and they have less reserve to waste away than do films of more suitable thickness (7). It is therefore not surprising that they erode unnecessarily rapidly.

On the other hand, unduly thick coatings are prone to bad behavior (16, 17). Cracking often appears earlier, is coarser in pattern and more conspicuous than is normal for the kind of paint, and very often is oriented across rather than with the grain of the paint coating. The coarser cracking leads to unsightly scaling that is unrelated to the summerwood pattern of the wood surface. Such scaling occurs about as early on the woods that hold paint best as it does on the more exacting woods. For each kind of paint there seems to be a critical thickness of coating above which the abnormal behavior sets in. The critical thickness is as little as 6 to 8 mils for the paints that swell greatly in water and form brittle coatings of high strength in tension, whereas it is as great as 15 mils for low-swelling paints that retain plasticity longer and have moderate strength in tension.

Modern practices in paint maintenance tend strongly to build unduly thick coatings after a few repaintings. The paints in predominant use, which erode at the slower rate of 0.4 mil a year when fully exposed to the weather, require 5 years or more to wear sufficiently to accept one good coat of new paint without adding appreciably to the total thickness of coating, yet they are often repainted at intervals as short as 3 years of even less, sometimes with two new coats at a time. A few repaintings suffice to bring the coating thickness above the low critical thickness of such paints. The curious anomaly exists that, in former times, when the paints in predominant use lost 0.7 mil a year and had a higher critical thickness, the customary intervals between paintings were considerably longer and the abnormalities of unduly thick coatings were seldom encountered.

Incomptabilities Among Paints: Abnormalities often develop when houses are repainted with a kind of paint that differs too much in some of its properties from the paint used previously. The reason for such incompatibilities were obscure until the swelling effect of water on different paints became known. The junction between coatings of markedly disimilar swelling capacity necessarily becomes the seat of very high stresses when the coating absorbs water and dries out again. Moreover, the adhesion of one coat to the other is impaired by water, just as is the case with the adhesion of paint to wood. Heterogeneous free films that consist of a coat of high-swelling and a coat of low-swelling paint curl into tight scrolls when soaked in water, and after somewhat longer soaking they will often blister and come apart easily. Such heterogeneous coatings on houses may crack, curl, and scale from the wood interface abnormally soon or, in more severe cases, the outer coating may crack and scale from the inner coating. Still another variant is alligatoring, in which the outer coat cracks in a reticulate pattern and then shrinks in area, so that the cracks open into relatively wide gaps and the polygon-shaped islands of topcoat may become wrinkled.

In at least one case, dissimilarity between coats proves advantageous rather than harmful. It is now recognized that, when suitable house-paint primers are used under finish coats that contain zinc oxide, the improved performance obtained comes in part from the fact that the primers are usually made without zinc oxide and at relatively high pigment volume and therefore have low swelling capacity. The low-swelling priming coat buffers the swelling tendencies through the coating by minimizing the strain at the interface between wood and paint without too greatly increasing the strain at the interface between paint layers.

Blistering: Paint blistering can occur in several different ways. A necessary condition that they share in common is the development of pressure in a gas or liquid at the interface where the blisters arise.

In temperature blistering, the pressure comes from thermal expansion of air in a porous substrate under the coating. A fairly frequent example occurs when houses are repainted in weather when days are warm and sunny but nights are cool. New paint applied perhaps in the afternoon becomes blistered next morning soon after warm sunshine strikes the surface. Air in the wood expands with warmth and pushes through tiny cracks in the old paint to press against the new coating at a time when its outer skin has hardened but its deeper parts are still soft. Even well-weathered paint may be blistered if the surface is struck by a sudden blast of heated air. Practical use is made of temperature blistering when old paint is removed with a painters' blow torch.

In "glossy-back" blistering, the pressure comes presumably from the gases evolved by deterioration of old paint that has been barred from access of oxygen and ultraviolet light by coatings subsequently applied. Such blisters are characterized by the presence of a transparent, glossy, sometimes sticky material that looks like old varnish on the back of the blisters and on the surface underneath. The glossy material is at least partly soluble in water, and seems to be identical with the material extracted from paint film by water. Events that finally result in glossy-back blisters begin with a yellow or brown discoloration of a layer of the old paint, followed by formation of holes with smooth, glossy walls that look under a microscope like the holes in Swiss cheese. The holes gradually grow larger, join together, and finally form large cavities that become blisters. The glossy material accumulates in a relatively deep portion of the film, perhaps because the thickness of the coating makes its extraction by rain difficult. The deposits may then prevent the ready escape of decomposition gases. There are times, however, when the glossy material exudes from paint coatings and discolors the exposed surfaces or even collects in beads or droplets that can be easily mistaken for wood resin.

The source of pressure in moisture

blistering has not yet been established satisfactorily. It may not be the same in all cases. Pressure may develop in the air in the wood under the coating from thermal expansion or when a wet line in the wood advances toward the coating under a temperature gradient, thereby squeezing the trapped air against the back of the coating. Soluble substances in the paint next to the wood may give rise to osmotic pressure, with the coating acting as a semipermeable membrane. The source of pressure may differ with circumstances, and there may be more than one source in a given case. But unless water in the form of liquid reaches the wood-paint interface, the pressure required to blister well-dried paint coatings is usually very great, often of the order of 500 pounds per square inch (34). Water at the interface is necessary as a rule (47) for moisture blistering, because it weakens the adhesion so much that pressure as low as 15 pounds per square inch (34) may suffice.

Water can reach the interface readily if it enters in sufficient quantity from the unpainted edges or backs of boards. Movement toward the interface between the wood and paint is hastened if the painted face is much colder than the back of the board, but moisture blistering can develop without such temperature gradient (47). On houses, moisture may gain access behind painted woodwork by cold-weather condensation of vapor that originates inside the house. It may also enter from the outside by penetration through joints. The latter is probably the more common cause, but it is often overlooked because cold-weather condensation has been so widely publicized.

Blistering seldom occurs from water that reaches the paint-wood interface through the paint coating alone. Water moves through paint so much less rapidly than it does through wood, and there is usually so much more wood than paint present, that the dry wood keeps the paint at the interface reasonably dry for a longe time. Water does blister paint on non-absorptive substrates such as glass or metal and probably does so on wood if there is time enough for the wood to come to its fiber saturation point. Even free paint films may blister when soaked for several days.

Tests on laboratory blistering boxes, in agreement with long observation of experience on houses, prove that some paints are more sensitive to moisture blistering than others. There is a close parallel between the degree to which paints absorb water and swell and their sensitivity to moisture blistering. The sensitive paints are the high-swelling paints. Resistant paints are low in swelling. When high-swelling paint is used for the finish coat, the sensitivity to blistering is reduced if a low-swelling priming coat is interposed between wood and finish coat.

Conclusion

Study of the mechanisms of paint deterioration reveals that water must be considered a major destructive agent along with ultraviolet light. Water alone, but even more in conjunction with ultraviolet light, accelerates deterioration chemically by stimulating production of volatile and water-soluble decomposition products that have much to do with the various stages of both normal and abnormal behavior of house paints. Water also attacks physically by swelling coatings and then causing severe internal stresses as the coatings dry and shrink again. The stresses disrupt coatings in one way or another. Water is also involved in the self-cleaning action of paints that has been so greatly emphasized in recent years. In the effort to make modern paints as clean as possible, they have been made increasingly sensitive to the harmful attacks of water. A current trend to the manufacture of paints that are more resistant to water is highly encouraging. But there is still need for more research on the mechanisms by which water attacks paint and means of controlling them, so that more reliable paints can be produced.

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Wood Moisture Content in Homes

SEASONAL VARIATIONS IN THE SOUTHEAST[1]

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Largest changes in moisture content occur during spring and fall. Wood in basements may vary up to 12%; in attics and living areas, changes are less. House construction, insulation, and heating system have little effect. Next step is to evaluate effect of finishes.

Typical of the southeastern homes in which moisture-content-variation samples were placed for study.

ONE OF WOOD'S most interesting and perplexing properties is its ability to absorb and lose water and water vapor with changes in temperature and humidity. When absorbing or releasing moisture between 0 and about 30 percent moisture content (known as the fiber saturation point), wood swells or shrinks.

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To further complicate matters, wood does not increase or decrease in dimension uniformly. Dimensional changes in length or along the grain are very slight, while the dimensional changes in width across the grain are large (as high as 14 percent from ovendry to fiber saturation). Dimensional changes in thickness are usually about half as much as across-the-grain movement. These unequal dimensional changes in the length, width, and thickness of wood are a constant problem to furniture manufacturers and other users of wood.

Because of these unique properties, moving wood parts such as drawers, doors, and windows tend to tighten and loosen or even check or split with changes in weather conditions. Wood in fixed positions, such as flooring and structural house members, may shrink and swell enough to cause opening and closing of floor joints, separation of window framing, and even cracking of wall plaster. Where grain distortion or abnormal wood is present, wood will bow and twist with moisture changes.

[1] Presented at the Fall Meeting of the Carolinas Chesapeake Section, FPRS, Nov. 7, 1958, in Charlotte, N. C.

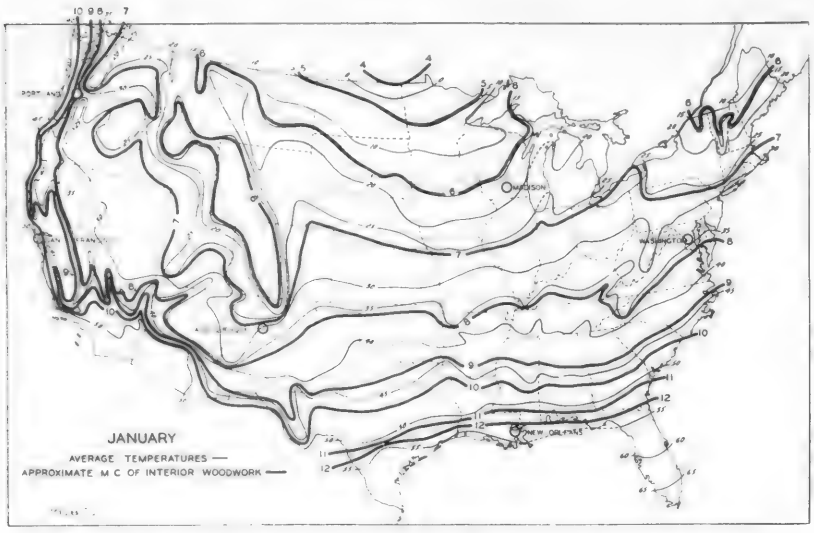

Fig. 1.—Relation of moisture content of interior woodwork to outdoor temperature of various areas of the United States in January.

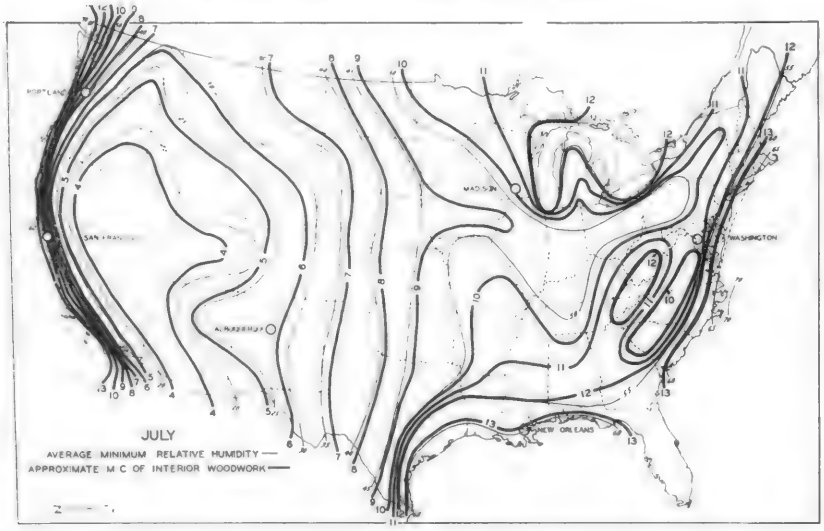

Fig. 2.—Relation of moisture content of interior woodwork to outdoor relative humidity of various areas of the United States in July.

To minimize this problem, wood workers and manufacturers attempt to fabricate their product at a uniform moisture content, which is usually the average of the seasonal range. For instance, furniture in the midwest may be fabricated at 8 percent moisture content since this represents the mid-range between 6 percent during the winter months and 10 percent during the summer months. Likewise, furniture in Florida may be fabricated at 12 percent moisture content to suit the average for that area. All over the country, wood products are usually assembled at predetermined moisture contents in an attempt to make wood give its best performance in use. This is not always achieved.

The Forest Products Laboratory, in an effort to help solve this problem, made a study of the moisture content of wood in dwellings in representative cities throughout the United States[2], and as a result divided the country up into three areas on the basis of climate and interior heating practices. The report gives maps of the U. S. that show isobar-like lines of relative humidity, moisture content, and temperature in January and July (Figs. 1 and 2). This information has been invaluable, but the need for more localized information prompted the California Dry Kiln Club and the Southeastern Dry Kiln Club to undertake further studies.

The Southeast has long been a furniture-making center, High Point, North Carolina, being known as the furniture center of the world. The long-felt need for specific moisture content information in this area prompted the Southeastern Dry Kiln Club to launch a study to determine

[2] E. C. Peck. Moisture content of wood in use. U. S. Forest Prod. Lab. Rpt. No. 1655. 1955.

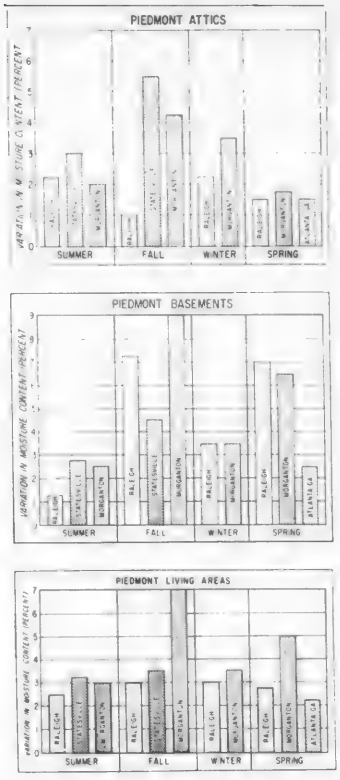

Fig. 3.—Moisture content variation was highest in the fall and spring in home interiors of the piedmont and mountains (Fig. 4).

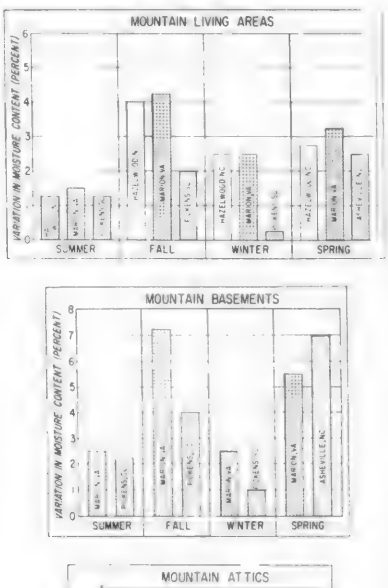

Fig. 4.—Higher variations in the fall and spring are due to humidity changes caused by turning heating plants on and off during these two seasons.

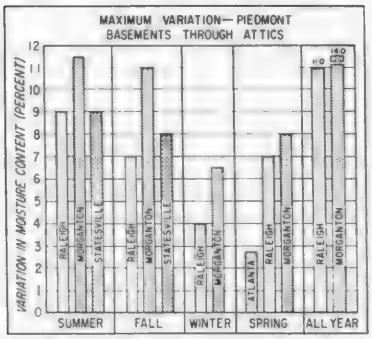

Fig. 5.—Winter is the season that shows the least moisture content variation from attic to basement in both the piedmont and mountains (Fig. 6).

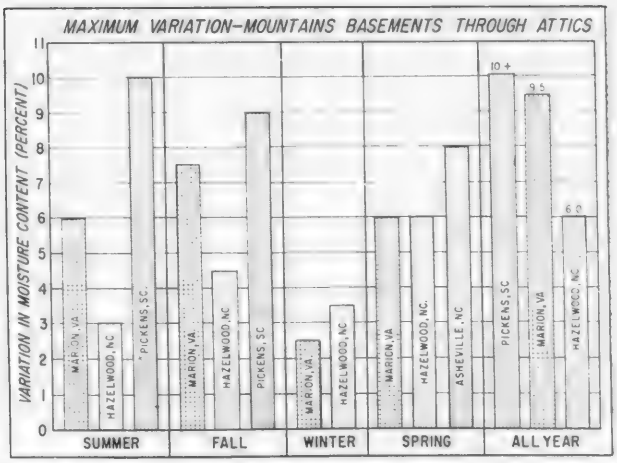

Fig. 6.—Probably because of colder winters with more heating required, the mountains showed only 3½ percent moisture content variation from attic to basement.

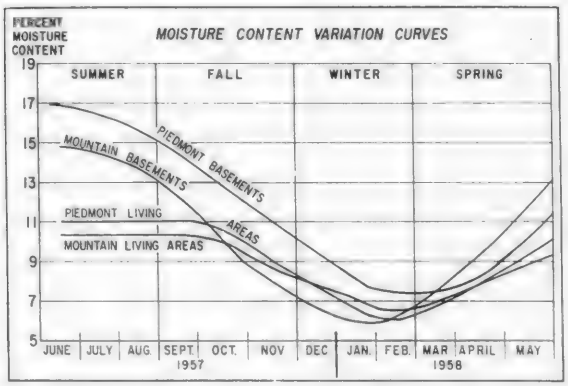

Fig. 7.—Moisture content curves were averaged for each area tested and show consolidation during wintertime and spreading during spring and summer. Notice the change in moisture content in piedmont and mountain basements.

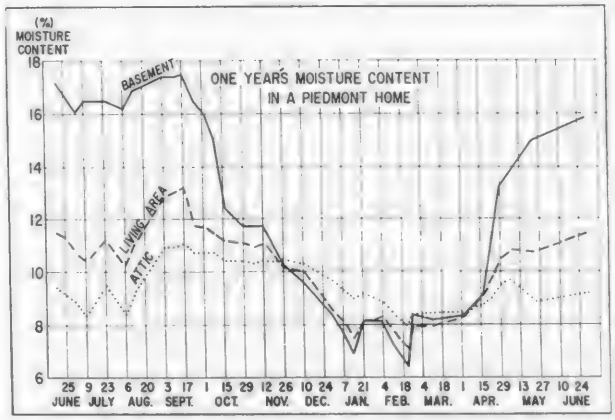

Fig. 8.—Data plotted for one year in a piedmont home show the wide variation in moisture content in the basement as compared to the more moderate changes in the living area and attic.

the moisture content variation in homes throughout the Southeast in June of 1957.

Procedure

Method of Study: Basswood specimens of predetermined ovendry weights were distributed in groups of three each to members of the club. These specimens were placed in the attic, living area, and basement of member's homes. Information on the type of home construction, type of heating system, and location of home were all recorded. Each week the specimens were weighed by the kiln club members and the weights were reported to Asheville, North Carolina, where moisture contents were calculated from the predetermined ovendry weights of the specimens. Moisture content variation was determined by subtracting the low from the high moisture content for the period being reported. Since the specimens had no finish applied to them, they were sensitive to small changes in moisture content.

From the unfinished specimens, moisture contents were determined for areas of the piedmont and mountains from Virginia to Georgia. A few determinations have also been made from as far south as Florida, and with interest in the study still growing, moisture content information will be strengthened with additional data through the coming year.

Discussion of Results

Moisture contents ranged from a low of 5 percent to a high of 19 percent, well within the realm of the active shrinkage and swelling range of wood and just under the threshold of any danger from decay. Since it is moisture content variation which governs the dimensional changes in wood, it will be given most of the emphasis in this discussion. In addition to the data on variation, ranges and averages of moisture content by year and season will be shown later.

Variation by Seasons: Of great interest was the seasonal moisture content variation found in the attics, living areas, and crawl spaces of piedmont and mountain homes (Figs. 3 and 4). Piedmont homes showed somewhat larger variations than did mountain homes. These figures also show that the largest variation occurred in the fall, regardless of the place in the home tested. This is the time of the year when the home-owner turns on the heating plant, with a subsequent drying effect upon the interior wood. The basswood specimens quickly reflect this drying condition, as the figures show.

As might be expected, basements showed the largest moisture content variation, as much as 9 percent in the piedmont compared to 7-¼ percent in

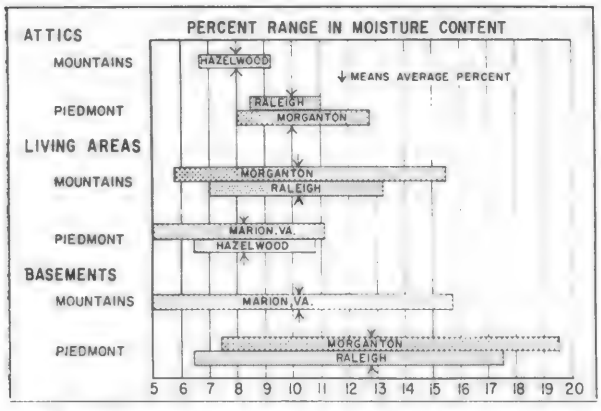

Fig. 9.—Moisture content ranges in the mountains and piedmont are shown in relation to each other. Average moisture contents are weighted by number of observations.

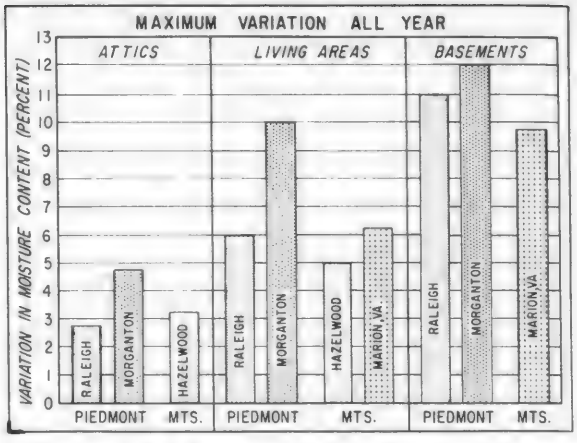

Fig. 10.—As before, piedmont home interiors show more variation than mountain home interiors. The amount of variation shown for the home interior is the maximum (high minus low) for the year.

the mountains. Spring is also a season of fairly rapid changes, they exceed winter and summer in this respect. Again basements were high, and showed as much as 7 percent both in the piedmont and mountains. In the spring, heating plants are gradually turned down, and the wood in homes increases in moisture content until it reaches equilibrium with outside air.

In addition to changes from season to season, the extremes in variation throughout a home from attic to basement are important (Figs. 5 and 6). The summertime difference between hot, stuffy attics and cool, damp basements proved to be large—11½ percent in the piedmont, and 10 percent in the mountains. The fall season is somewhat the same, it shows slightly less variation from attic to basement and winter shows the least. The last column of each of these two graphs summarizes the maximum yearly moisture content variation from attic to basement, and this yearly variation is always higher than any seasonal variation. The piedmont was high with 14 percent variation for the year in one home; the maximum in mountain homes was a little over 10 percent. Imagine what might happen to a piece of furniture stored in the basement and moved to the attic, or vice versa. The change in dimensions could amount to half of the total possible shrinkage or swelling of the wood.

Actual Moisture Contents: The extent to which moisture contents vary during the year in the piedmont and mountains is much greater than generally believed. Fig. E compares average moisture contents in living rooms and basements for individual areas for the entire year from June of 1957 to June of 1958. It can be seen from the curves that mountain home living areas show the least variation over the year, while basements of both piedmont and mountain homes show the greatest variation. Continuous records of attic moisture contents were not available for this chart.

Individual moisture contents were taken each week in one piedmont home at Raleigh, North Carolina (Fig. 8). This is a well-constructed brick veneer home. Actual moisture content ranges for attics, living areas, and basements for all houses studied are shown in Fig. 9. Piedmont and mountain areas are compared and average moisture contents for the year are shown. Again, the piedmont shows a larger *range* in moisture content variation and also a higher *average* moisture content.

Maximum Variation for the Year: Yearly variations are naturally greater than individual seasonal variations (Fig. 10). Basements vary 12 percent yearly in moisture content in the piedmond and 9-¾ percent in the mountains. The range in actual moisture content in one piedmont basement was from 7 percent in the dry of winter to 19 percent during the summer (Fig. 9).

Living areas showed less yearly moisture content variation and, of course, attics the least.

Because of the sensitivity of the basswood moisture-content specimens, weather changes could be detected easily. A few days of rainy weather started moisture content curves in an upward trend throughout the rainy area. Likewise, the week the furnace was turned on in a home, the basement moisture content specimens began a steady drop in moisture content.

The very fact that the basswood specimens were so sensitive to humidity changes invites caution in interpreting curves of moisture content variation. Certainly homes of different types of construction with and without insulation and the variations in home heating play a part in determining wood moisture content at any particular time. Not enough information has yet been received to make any definite conclusions about average moisture contents and how they are affected by types of home construction and heating plants.

Plans for Next Year: To learn how finished specimens simulating furniture react, the club will install a new set of furniture-finished specimens to be measured along with the initial set. In this manner, not only the highs and lows of moisture content variation will be recorded, but also the reduced variation caused by the partial surface-sealing-effect of commercial finishes will be determined. Moisture content results from this set of specimens will be reported at a later date in further progress reports.

Conclusions

With limited data obtained in the Southeast, it has been demonstrated that moisture content of wood in homes can vary widely by seasons of the year and in different parts of a house. These variations are controlled to some extent by house construction, insulation, and heating systems, but in the best of houses, unfinished wood can change in moisture content enough to cause serious damage to wood products. the next step is to ascertain the effect of finishes in retarding such changes, and to develop recommendations not only on the factory moisture content of wood products but also on the methods to prevent changes that cause damage in the home.

Adhesives for Dissimilar Materials[1]

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ADHESIVES FOR DISSIMILAR MATERIALS is an extremely broad subject that can embrace virtually all of the many types of adhesives available, as well as nearly all the types of materials that are amenable to adhesive bonding. Actually, there are probably more useful adhesive bonds involving dissimilar materials than there are involving similar materials, and a great many adhesives can be used to bond dissimilar, as well as similar, materials.

From a practical standpoint, the important dissimilarities are those that affect to a significant degree the performance of the bonded joint, and, since each specific adhesive application is indeed an individual case with individual problems, the number of factors to be considered could be quite large. This report, however, is limited to some of the more frequently encountered dissimilarities, which can be classified roughly as chemical dissimilarities and physical dissimilarities.

Chemical dissimilarities to be considered are those that have to do with adhesion, with the effect of the adhesive composition on the material to be bonded, and with the possibility of galvanic action in metal-to-metal bonds. Physical dissimilarities of importance are those that control relative changes in dimensions of the bonded members: (1) thermal coefficient of expansion, (2) tendency to expand and contract due to changes in moisture content, and (3) modulus of elasticity, which is a measure of the rate of change in dimensions with applied stress.

A wide variety of both natural and synthetic adhesives are available on the market, and it might be interesting at this point to indicate one possible broad classification of adhesives based on composition. The following tabulation provides such a classification.

CLASSIFICATION OF ADHESIVES[2]

1. Naturally-occurring materials
   a. Starch and dextrins (from vegetable sources)
   b. Proteins (from both vegetable and animal sources)
      (1) Animal (bones, hides, sinews)
      (2) Blood (whole blood or albumin)
      (3) Casein (from milk)
      (4) Soya-bean protein
   c. Other materials
      (1) Asphalt
      (2) Shellac
      (3) Natural rubber (including reclaimed rubbers)
      (4) Sodium silicate
2. Synthetic polymers
   a. Thermoplastic (cellulose esters and ethers, alkyd and acrylic esters, polyamides, polystyrene, synthetic rubbers, polyvinyl alcohol and derivatives)
   b. Thermosetting (urea, melamine, phenol, resorcinol, furane, epoxy resins, synthetic rubbers)

Consideration must be given to the materials to be bonded, anticipated service conditions, and desired service life. Adhesives must adhere to both materials, and they must not adversely affect adherends during bonding. Bonded members preferably should be inert to each other.

There is no separate and distinct class of adhesives that is used solely for the bonding of dissimilar materials. Rather, the bonding of each combination of materials must be considered as an individual case with due consideration for the properties of the materials to be bonded, the anticipated service conditions, and the desired service life. In choosing adhesives for bonding materials with dissimilar dimensional-change characteristics, the thermoplastic synthetic polymers are probably of most interest, since they inherently are more capable of adapting themselves to the changing dimensions of the bonded materials. Many of the naturally-occurring materials and the thermosetting synthetic materials are too rigid for such use.

Dissimilar Chemical Characteristics

Adhesion: Adequate adhesion to both surfaces to be bonded is a fundamental requirement, and it is well known that the chemical compositions of both the adhesive and the materials to be bonded are important factors in determining the degree to which an adhesive bond will be formed. Few adhesives bond well to all materials, and it is important in each individual case to select an adhesive that will bond to both materials involved. For example, in the bonding of nitrile–butadiene rubber stock to metal, it has been found that adhesives composed of neoprene rubber are not suitable because, while they adhere well to the metal, they do not adhere to the nitrile stock. If, however, an adhesive composed of nitrile–butadiene rubber is used, it will adhere to both the nitrile–butadiene stock and the metal. Similar problems arise in the bonding of "difficult" materials, such as polyethylene and Teflon, and it is often necessary to resort to the use of very soft adhesives with low cohesive strengths or to the use of special surface treatments.

All of the factors that contribute to adhesion are not thoroughly understood, but it is probable that all types of molecular forces capable of causing intermolecular attractions can be involved, depending upon the natures of the particular adhesive and the materials to be bonded. Wetting of the surface by the adhesive is, of course, a primary requirement, and it is likely that wetting is an indication of molecular attraction.

As yet, no precise quantitative correlation can be made between molecular quantities and adhesion, and at the present time the scientist can be of little help to the technologist in the matter of predicting adhesion. It is, therefore, necessary to rely on either experience or trial-and-error in the matter of achieving adequate adhesion.

Effect of the Adhesive Composition on the Material to be Bonded: Because of dissimilarity in chemical

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[1] Presented at FPRS Northeast Section Meeting, Oct. 30-31, 1958, Lancaster, Pa. Submitted to Journal Nov. 13.

[2] Clark, Rutzler, and Savage (editors). 1954. Adhesion and adhesives: fundamentals and practices. John Wiley & Sons. pps. 74-80, Types and uses of adhesives. R. F. Blomquist.

composition, two materials to be bonded often vary widely in susceptibility to attack by adhesive solvents. Some materials, notably wood, cork, and certain metals, may be adversely affected by water. On the other hand, rubber and many plastics are susceptible to attack by organic solvents. Since most adhesives contain either water or organic solvents, problems can arise in the bonding of solvent-susceptible materials to those susceptible to attack by water.

Such a problem is encountered in the bonding of foamed plastics to steel. Many water-soluble or water-dispersed adhesives do not adhere well to metals, and in some cases they might even be responsible for corrosion of the metal. On the other hand, certain foamed plastics are dramatically affected by solvents. When a solvent-type adhesive is applied to a piece of foamed polystyrene, the result is immediate collapse of the foam. In contrast, polyether foams swell in contact with solvents. A number of techniques can be used to solve this problem. One of the possibilities involves the application of a solvent-type adhesive to the metal, and a water-dispersed adhesive to the foam. The two adhesive films can be combined to form a useful bond when most of the water and the solvent have evaporated, and the adhesive films are in a tacky, but not wet, condition.

Galvanic Action: The next tabulation presents a galvanic series of common metals and alloys. Metals high on this list are chemically more reactive with respect to oxidation-reduction reactions than are those further down on the list. In metal-to-metal bonding involving metals with different positions in the galvanic series, the possibility for galvanic action exists, with the resultant rapid corrosion of the more active metal. This corrosion is capable of destroying adhesion to the metal. Therefore, the possibility of galvanic action should be considered in all cases where dissimilar metals are joined. It is possible to reduce the risk of galvanic action by using an adhesive with good electrical insulating properties and making certain that the metals themselves are not in contact.

GALVANIC SERIES OF METALS AND ALLOYS

Magnesium and magnesium alloys
Zinc
Aluminum 2S
Steel or iron and cast iron
Chromium iron (active)
18–8 Cr–ni–Fe, 18–8–3 Cr–ni–Mo–Fe (active)
Lead–tin solders, lead, and tin
Brasses, copper, bronze, copper–nickel alloys, and titanium monel

Thermal Coefficient of Expansion: The relationship between the thermal coefficients of expansion of the two materials to be bonded is an important matter for consideration where dissimilar materials are involved. Some thermal coefficient values for a variety of materials follows:

Steel	0.063
Steel (18–8st)	0.096
Bronze	0.100
Aluminum	0.130
Concrete	0.080
Masonry	0.025–0.050
Plate Glass	0.050
Marble	0.020–0.090
Wood (Oak)	0.030

Ideally, the thermal coefficients of expansion of two materials to be bonded should be the same, if the bond will be subjected to varying temperatures in use. The more closely the coefficients correspond, the less likely it is that difficulties will be encountered. For example, there is less likelihood of difficulty in wood-to-steel bonds than there is in wood-to-aluminum bonds.

When bonded sheets of materials with dissimilar thermal coefficients of expansion are subjected to temperatures higher than those at which the bond was made, one of the materials will expand more than the other, and the unequal expansion will tend to set up shear stresses at the interface between the adhesive and the bonded surfaces. Unless the adhesive is capable of stretching, bond failure can occur. In general, it is the soft, low-modulus adhesives that are capable of adapting themselves to the new configuration of the system with a minimum of residual stress.

If large, flat sheets of flexible materials are involved, usually the unequal expansion will result in bowing with the material having the larger coefficient on the convex side. This bowing tends to relieve stresses in the adhesive to some degree. However, bowing is usually undersirable and, in many cases, it can be prevented by sandwiching one of the materials between two of the other to form a balanced construction. If this is done, the joint may remain flat, but the bond will be stressed. In this case, the adhesive must flow or stretch to relieve the stress.

Expansion and Contraction due to Changes in Moisture Content: Materials composed of wood, cork, and asbestos tend to be hygroscopic and will absorb moisture from the atmosphere. In so doing, they expand and to some degree are themselves reduced in strength. When a hygroscopic material, such as wood, is bonded to a non-hygroscopic material, such as metal, large changes in humidity will cause expansion of the wood and tend to set up shear stresses in the bonded joint similar to those caused by thermal expansion. Here again, a soft, low-modulus adhesive is more capable of absorbing the stress than is a rigid adhesive.

Laboratory test procedures have been devised to test the abilities of adhesive-adherend combinations to withstand stresses due to dissimilarity in dimensional change characteristics. Such procedures involve subjecting the bonded joint to a series of differing temperature, humidity, and moisture conditions, usually on a cyclic basis. The following cycle, ASTM D–1037, is widely used in the building panel industry.

Each cycle consists of:

a. Immersion in water at 122°F for 1 hour.
b. Spraying with wet steam at 194°F to 200°F for 3 hours.
c. Exposeure to 10°F for 20 hours.
d. Exposure to dry air at 212°F for 3 hours.
e. Spraying with wet steam at 194°F to 200°F for 3 hours.
f. Exposure to dry air at 212°F for 18 hours.

This series is repeated until the specimen has been exposed to a total of six cycles.

Notice that this test introduces the effects of thermal shock in combination with alternate wet and dry conditions. Where the bonded materials have dissimilar coefficients of thermal expansion, the differences in expansion and contraction must be taken up by the adhesive. The alternate wet and dry conditions have a similar effect where hygroscopic materials, such as wood, are involved. While cycles of this type are most useful in comparing different adhesive-adherend combinations, they are of lesser value in predicting absolute performance of the given combination.

Test results obtained by the use of this cycle have shown that the relatively low-modulus, thermoplastic adhesives are better able to adapt to the differences in dimension brought about by changes in temperature and humidity than are rigid thermosetting adhesives. For example, 12- by 12-inch panels consisting of hardboard cores with porcelain enamel steel skins and galvanized steel backings consistently undergo delamination in less than six cycles of D–1037, if bonded with thermosetting resin adhesives or epoxy adhesives, but the panels will successfully withstand six cycles of this test when bonded with thermoplastic neoprene-phenolic resin adhesives.

There is an interesting relationship between the specimen size and the effect that cycling has on a given combination of panel components. While

relatively small, 3- by 12-inch, specimen will undergo six cycles of D-1037 with no sign of delamination, a 12- by 12-inch specimen of the same components will occasionally show some delamination. The effect is more pronounced in 4- by 8-foot specimens. Apparently, the effects of the dimensional change are more pronounced at the edges of the specimen than the center, for it is here that delamination occurs first. Therefore, it becomes extremely important that tests be conducted on full-size specimens. In some cases, this size effect can be minimized by designing the panels in such a way as to prevent the accumulation of large stresses. Possible solutions to this problem include the use of alternating bonded and unbonded areas, and the use of expansion joints.

Modulus of Elasticity: In some adhesive applications, the principal function of the adhesive is simply to hold the parts together, and there may be little likelihood of stresses on the bond other than those that are inherent from the nature of the bonded materials. In other applications, however, the bond must withstand externally applied stresses. This latter type of application is of interest here.

The elastic moduli of adhesive and adherends play an important part in determining the ability of adhesive bonds to withstand external stresses. Ideally, the modulus of the adhesive should be the same as that of the adherends. This can rarely be achieved, but it is preferable that the modulus of the adhesive be smaller, rather than larger, than that of the bonded materials. When relatively high-modulus adhesives are used to bond low-modulus materials, the bond is predisposed to failure under small shear stresses. When shear stresses are applied to such a bond, the bonded material will stretch to a greater extent than will the adhesive. This condition will result in large shear stresses at the interface between the adhesive and the bonded materials.

In bonding materials of widely different elastic moduli, it is desirable that the modulus of the adhesive not be larger than that of the bonded material having the lower modulus, if the bond is to be stressed in shear. If, however, impact stresses are involved, a more rigid higher-modulus adhesive will generally be satisfactory, since the low-modulus bonded material will absorb the impact. This situation occurs in applications involving rubber-to-metal bonds.

Strength of a Bonded Joint: The degree of strength actually required in a bonded joint is difficult to determine in advance in most cases. The bond must be sufficiently strong to withstand the combination of externally applied stress and internal stresses due to differences in expansion and contraction of the bonded members. In addition, it must be sufficiently strong to provide a reasonable margin of safety.

It has been the accepted practice to measure adhesive strength by the use of some form of testing machine, and many standard testing procedures are written around the use of such machines. One of the disadvantages of these procedures is the difficulty of interpreting the strength values obtained by machine testing in terms of the usable strength of an adhesive bond. A typical joint prepared with a thermoplastic adhesive might show a strength of 1,500 psi tested to destruction in a testing machine, but it is likely that this bond would fail in a few hours under a sustained load of 1,000 psi. The maximum load that an adhesive bond will sustain for an indefinite period without failure or excessive creep must be known. In this case, the maximum might be of the order of 500 psi or even lower. It is apparent that this latter *static-load value* of 500 psi more nearly represents the maximum usable strength of the adhesive. It should be pointed out, however, that this maximum static-load value is not a constant for a given adhesive under all conditions, but that it depends greatly upon the temperature at which it is determined, as well as upon other factors. Well-cured thermosetting adhesives generally retain a higher proportion of their machine strength as usable strength than do thermoplastic adhesives. A typical thermosetting adhesive that has a machine-measured strength of 3,000 psi might have a static-load strength of 2,000 psi.

As stated above, the strength value for an adhesive bond is dependent on the method by which it was obtained. Some of the factors that influence the measurement of bond strength are listed below:

1. Nature of the bonded materials.
2. Method of preparation of the bond.
3. Conditioning of the bonded specimen prior to testing.
4. Temperature at which the test is conducted.
5. Type of stress applied; tensile, shear, peel, etc.
6. Rate of application of the stress, or duration of the stress.

While it is beyond the scope of this paper to discuss the above factors in detail, it might be of interest to point out some of the effects of temperature on adhesive bonds, since there is an increasing demand for adhesives that will withstand very high or very low temperatures.

Thermosetting adhesives show better high-temperature properties than do thermoplastics, but some thermoplastics are useful for intermittent high temperatures where extremely high strength is not required. The following tabulation shows some typical shear-strength values obtained with both thermosetting and thermoplastic adhesives at room temperature and at 180°F. The values were obtained on ½-inch overlap specimens of aluminum bonded to aluminum and tested at a machine speed of 0.05 inch per minute.

SHEAR STRENGTH AT 70° AND 180° F.

	70°F	*180°F*
J-1151 (Thermosetting Adhesive) ------	3,200 psi	2,000 psi
D-253 (Thermoplastic Adhesive) ------	1,259 psi	58 psi

The behavior of adhesives at low temperatures is also of interest. Some thermoplastic adhesives have higher shear strength, but lower impact strength at —65°F than at 70°F.

The increase in shear strength at low temperatures is probably related to the increased stiffness of the adhesive film at low temperatures, and the decrease in impact strength is due to embrittlement of the film.

Summary

In bonding two materials that undergo unequal dimensional changes under such conditions as changing temperature, changing moisture content, or applied stress, it is necessary to use relatively soft, low-modulus adhesives, since these are inherently more capable of conforming to the changing configuration of the bonded joint than are rigid adhesives, thus minimizing shear stresses due to expansion and contraction.

In general, thermosetting adhesives have better static-load properties, better high-temperature properties, and better chemical resistance than do thermoplastic adhesives. On the other hand, the properties of thermoplastic adhesives are frequently more than adequate for many applications; and, in addition, they frequently show better low-temperature properties than do thermosetting adhesives.

STRENGTH OF NEOPRENE ADHESIVES AT LOW TEMPERATURES

	D-281		*D-239*	
	70°F	*—65°F*	*70°F*	*—65°F*
Dynamic Shear Strength (psi) ½ in. overlap, A1/A1, 0.05"/min. ----------	514	1839	888	1227
Impact (Ft. lbs./sq. in.) Charpy Impact Tester ----------	44.3	12.0	39.0	14.0

THE CINCINNATI PLAN:

Co-Operative Education

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In the co-op system, the student gets job experience, in alternating periods of school and work, in the industrial field he plans to enter. Four essentials are that the employer designate only one person in charge of co-op training; a definite course of correlated work be mapped out in advance; a definite wage scale be set up; and, if continuity is desired, a certain number of new co-ops be added in April and June each year.

CO-OPERATIVE EDUCATION was born in 1906, at the University of Cincinnati. At present, about 60 major schools use it in one form or another. It operates on the theory that engineers, for example, need practical experience as well as theory; and that the best time to start getting the required experience is during the students' college days—their formative years. By starting off at the bottom of the ladder, students become familiar with engineering problems gradually, at a time when they can see the application of theory while it is still fresh in their minds. Moreover, as they see the connection between theory and practice, class work takes on new significance.

Co-ops are usually assigned in pairs. At the University of Cincinnati they "alternate" in 8- or 10-week periods, and there are 11 work periods spread over 5 years. Together, a pair of co-ops is the exact equivalent of a full-time employee; there is never a time when the employer is scheduled to have both the men at work, and there is never a time when he has neither of them on the job. He always has one or the other, even during school vacations.

Four Essentials

To insure best results four essentials are recommended, namely: 1) that the employer designate one, and only one, person to be in charge of his co-ops; 2) that a definite course of correlated work be mapped out in advance; 3) that a definite minimum wage rate be worked for each successive work period; and that 4) if continuity is desired, as it usually is in larger companies, a certain minimum number of new co-ops be added in April and June of each year. (Special plans for smaller companies will be mentioned later on).

Administrative Control

The employer's designated "Supervisor of Training" should be selected with great care. He should be definitely interested in co-op training. He should have sufficient authority or backing to see that the employer's program is carried on throughout the plant. A "Co-ordinator" from the University will assist the Supervisor by visiting him from time to time. The Co-ordinator and the Supervisor have complete and exclusive jurisdiction over the co-op's training, the former over the academic phase, the latter over his activities as an employee. The student should be directed to consult his Co-ordinator, however, and not the Supervisor, in all matters having to do with rate changes, personal complaints, requests for job changes, and the like. The Co-ordinator will then decide whether it is necessary or advisable to discuss the situation with the Supervisor. Conversely, the Supervisor is urged, as a general rule, to call the Co-ordinator when various situations arise, and to deal directly with the student only for minor details.

Training Course

The definite basic course of work in the factory is laid out wholly by the employer. He decides what background he thinks his co-ops should have acquired by the end of their 11 work periods, and he lays out a work sequence accordingly, making use of jobs ranging from the freshman non-technical, or "familiarization-type" job, to the highest specialization the senior can handle. Ordinary employer-employee relations exist throughout. The University's Department of Co-ordination merely supervises the approved plan, and assists in adjusting the practical experience program so as to parallel as closely as possible the theory the student gets in school. The training may be changed, of course, whenever the employer wishes, or when economic conditions make changes desirable.

The particular type of work to which any student is assigned should depend somewhat on his aptitude. For instance, some co-ops are at home with problems that have to be reasoned out; others like to pitch into plant problems. Some men excell in indoor work, some in outdoor; some are manually dextrous, others mentally proficient; some are quick and dynamic, others work with methodical accuracy. Hence the route a particular co-op takes through the training process need not be the same as that taken by others. Nevertheless, if the employer thinks a knowledge of certain types of work essential for all his trainees, each co-op should do those types of work, even though not particularly adapted to

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them. Many employers, in the first and second years, set up a standard training schedule for all-over-the-plant experience, and postpone until the last three years the specialized assignments to the kind of work in which the individual co-op will be engaged after his graduation. Note that even those students who may not be retained beyond the second year have given value received for their wages, and the employer has suffered no loss or expense.

This no-cost feature compares very favorably with the expensive much-used practice of sending teams of interviewers to college campuses to secure 20-minute interviews with young men who at the time of graduation are seriously interested in selecting a satisfactory employer. Interviewers have told me they figure that each new graduate hired as a result of such a procedure costs the employer more than $1,500.00. The co-op, on the other hand, costs nothing but wages, which we hope he earns. Moreover, the co-op is not unknown to his employer when he begins his after graduation employment, and the employer knows the particular *job* for which his co-op has been groomed. Both get their knowledge of each other from actual work contact; neither is going into a trial or probation period. When a co-op continues after graduation with his co-op firm, he merely stops going to school; he works full-time instead of half-time.

Freshmen at Cincinnati are not assigned to co-operative work until after they have passed satisfactorily four 7-week terms of academic work. Half the freshman class "goes on the co-op basis" in April, the other half in June. From then on, they get 11 work periods, seven of 8 weeks duration and four lasting 10 weeks each—96 weeks in all. One period comes in the freshman year, three each in the sophomore, pre-junior, and junior years, and one in the senior year. In January, *all* seniors return to full-time academic work. They complete the course about the fourth week in May. There are co-op schools where different schedules and procedures prevail, such as full-semester alternating periods, or two years of full-time school before the co-op phase begins .

The ideal training for the first-year co-op is the job that teaches him to work. Let him do common labor. Let him rub shoulders with workmen, where he can observe their point of view. Let him learn, from actual contact, how to get along with people. First-year jobs can be regarded as a proving period; the co-op must make good before he can hope for promotion. Incidentally, at Cincinnati, no co-op may quit his job for another job under any circumstances. He must stay at work until his Co-ordinator can arrange his replacement. Conversely, the employer is requested to arrange all terminations through the Co-ordinator, and if possible to allow the terminated co-op to finish out the current work period. During the first two years, the co-op need not be assigned to anything of a confidential nature; thus if for any reason he is terminated, no classified information goes out with him. After the second year, the co-op work may vary according to the tastes and abilities of the individual. If the co-op shows promise in research, production, or sales-service, the remainder of his program can be laid out accordingly. The best performance can be expected, however, if the program includes job assignments that offer a real challenge to the student. Although a normal program consists of 11 periods, any work program can be altered or condensed to fit the case of the student who enters an employer's program after having been employed as a co-op elsewhere.

Special Plans

Many special plans are in use. Some employers, because of lack of variety or opportunity, do not care to follow a five year program. Such employers may have jobs, however, which, though essential, cannot be filled from day-to-day applicants—jobs which offer no progressive training and no after-graduation possibilities. Two or three such jobs can be used in succession by the Co-ordinator, to give the student holding them a varied training. Assignments in all cases are for a minimum of three work periods, one year. All these remarks apply to the University of Cincinnati. Other schools probably handle many details differently.

In some cases, a co-op may work "without an alternate", which is to say that while he is in school, no one is on the co-op job. In other cases, especially where the job is far away from Cincinnati, a job can be manned on a double-period basis, whereby each man of the pair gets one 10-week and one 16-week period per year.

Summer jobs can be arranged by allowing one co-op (no alternate involved) to work from June 15 to November 1, 20 weeks, without interruption. This plan is particularly good for men between their junior and senior years. It constitutes a tryout period for co-op and employers who might be interested in each other after graduation. The summer-job schedule can also be used to start freshmen out in their home areas. Any kind of job that will expose the men to factory conditions is acceptable.

Wage Patterns

It is usually better in the long run if standard wage patterns are set up. There is no standard universal rate. Wages vary rather widely in different localities and in different industries. In all cases it is recommended that the employer pay his first-period co-op the starting rate for his own newly-hired day laborers. A rate is then set for the eleventh period somewhat lower than the rate paid engineers who have just graduated from college. The rates for the second through the tenth periods are then adjusted to show equal raise increments. Thus the co-op gets a standard automatic raise each time he reports for work; the paymaster knows this, and no reminders need be sent him. Wages are paid directly to the co-op; withholding taxes, social security, insurance, and like charges are deducted, just as they are for other employees. The amount of wages received has nothing whatever to do with the "degree of credit" the student receives for his co-op work. In fact, it is emphasized that wages are secondary—the by-product. A co-op's job is never changed merely to get him more wages. When times are good, as they have been, practically all co-ops meet their expenses through co-op earnings. Full employment is not guaranteed, however, and the University assumes no obligation to provide work that will pay the expense involved. Co-ops accept four-day weeks if everyone else is working four days; they accept pay cuts when everyone else gets a pay cut. Conversely, they expect to participate in all general raises. Under no circumstances does the University furnish cheap labor. It insists that at all times the co-op receive the same wage paid to other workers for the same or equivalent work.

Continuity of the Program

The continuity feature is characteristic of all long-range programs. If two graduates can be absorbed by the employer each spring, then at least two freshmen should be introduced into the program each year. Four pairs, one from each class, would normally be engaged in such a program. Each January the two seniors would come off the job for their regularly-scheduled full-time second term in school, and in the following April the pair of new freshmen would start co-op work, with everyone else moving up. The employer is under no obligation to keep his co-ops when they graduate, and the co-ops are under no obligation to stay. In the majority of cases, however, co-ops *do* stay with the co-op employer after graduation. Indeed, the student can hardly better himself, and the em-

ployer could scarcely secure elsewhere a newly graduated engineer, who already has 96 weeks of practical experience behind him—experience obtained in the employer's own plant.

Getting Started

Normally, getting a pair of co-ops started is not much of a problem for Cincinnati firms or for those out-of-town companies with which the University already has established co-operative relations. Personal Record cards, kept by each co-ordinator, reveal birthplace, height, weight, high school grades, previous work for pay, physical condition, interest in activities, financial status, family statistics, and many other details. Students with too low grades may not be placed at all; they are not regarded as being eligible. The Co-ordinator and the Supervisor of Training get together, and with cards, photographs, scholastic records, and other data, choose the men to be assigned. In some cases, personal interviews are arranged.

Placements out of town are sometimes a little more complicated. It is usually difficult, and perhaps not as satisfactory, to send any freshman to his first job assignment in an area where he will have to pay board and room. It is much better, both for the student and for the employer, if local talent can be used. Several ways to encourage high school graduates from given areas to enroll at the University of Cincinnati have been developed. The prospective employer plays an important part in the recruitment of outstanding prospects.

The first method of locating prospective students for a long-range training program is for the employer, possibly with the aid of the co-ordinator, to get in touch with the Principals and Counselors of the high schools within the area to be served. In various ways, the employer publicizes his interest in "sponsoring" high school seniors who are: 1) in the upper 10 percent of the class, scholastically; 2) interested in one of the branches of engineering the employer wishes to train; 3) prominent in school activities; and 4) at least open-minded about returning to the home area after they graduate from college.

The Principals and Counselors should be impressed with the advantages of going along with the program, and the seniors should be told what the employer is willing to do for them as long as their attitude and scholastic attainments in college are satisfactory. "Advance earnings" can be made available by the employer's hiring the seniors for the summer following their graduation from high school. Co-op employment, when the time comes, is promised to those whose grades at the University are better than average, and, of course, is subject to economic conditions. Copies of the proposed training program are usually made available, and permanent after-college employment is stressed as a prime objective. Of course, students "sponsored" in this manner are invariably assigned to co-op work with the sponsoring employer.

The second method of securing co-ops is to grant cash scholarships, as about 70 companies are now doing. The industrial scholarship is usually awarded after a series of rather stiff tests, especially in mathematics. One firm selects 6 men each year, and normally has about 40 candidates to choose from. The scholarship is supposed to take care of the student's expenses up to the time he goes on the co-op basis. Parenthetically, since tuition payments by the student comprise about 40 percent of what it costs the University for his year's training, many scholarship plans include also a donation of a like amount to the University.

Advantages of the Plan

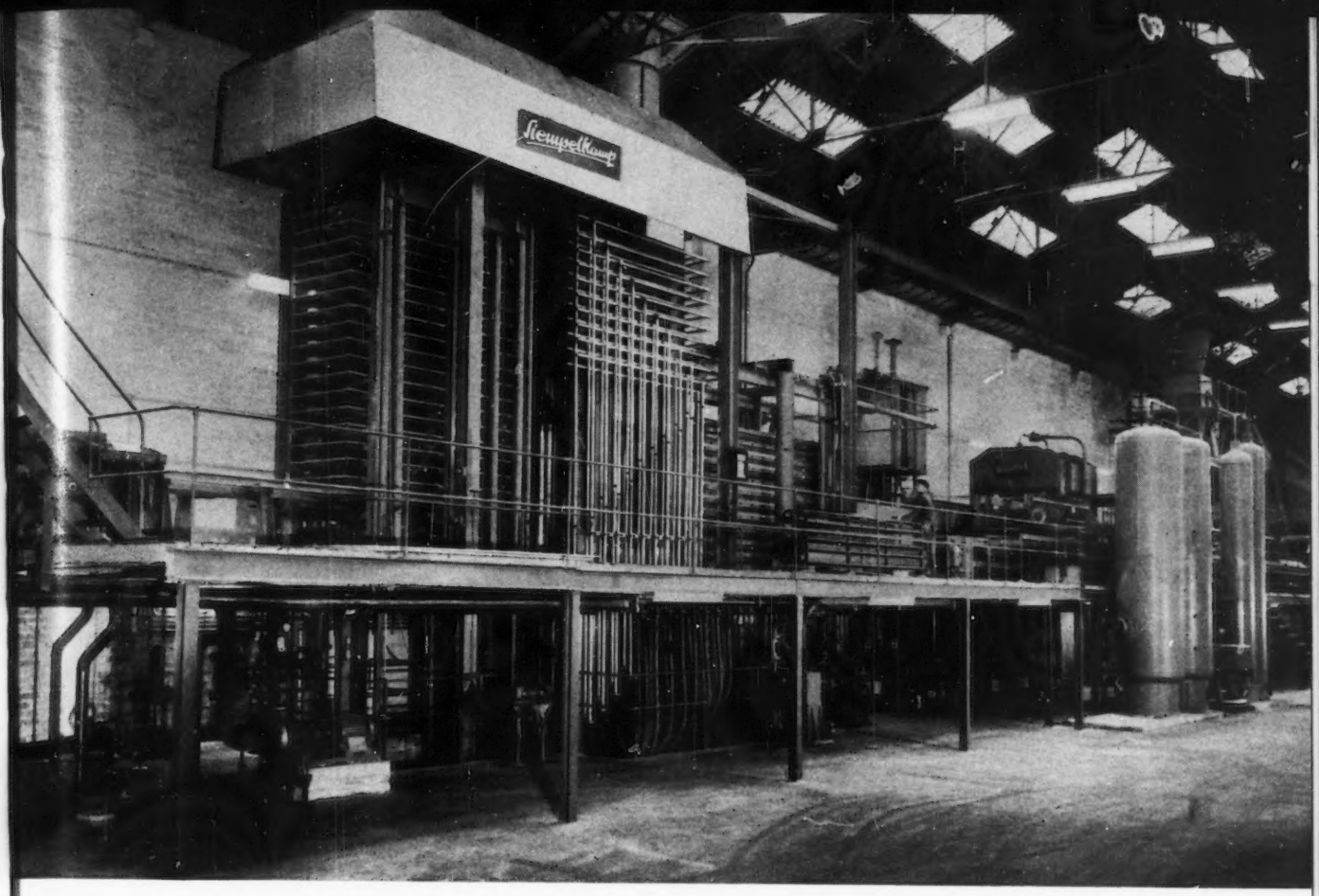
Now, let us talk about the advantages of the regular co-op plan; to the University, to the employer, and to the student. The University benefits from the fact that, with a given set of facilities and a given faculty, approximately twice the number of students can be accommodated. Since co-ops work for companies whose equipment must be up to the minute, the University is relieved of the necessity of purchasing expensive machines, which would be obsolete within a few years. Industry, however, must recognize obsolescence and set up reserves for replacement of out-of-date machines. The University can use industry's constantly modernized laboratory without expense. In addition, the University is more closely integrated with the community through the many contacts that result from employment arrangements with industry. The University's faculty is of necessity up-to-the-minute concerning industrial practices and development. Indeed, the faculty members at a co-op school cannot rely entirely on text books, when the students in their classes are in daily contact with industrial reality.

The employer secures engineers who, at the time of their graduation from college, are already adjusted to engineering requirements by gradual and everyday transition from academic pursuits to the actual environment of industry. Co-op schools like to feel that such men become available to the employer at practically no cost, since the co-op is assumed to *earn* his wages. Industry also benefits by having a constant source of supply of superior trainees. All Engineering co-ops are upper-third high school graduates; all are definitely interested in the courses they have chosen; and all are activated by the knowledge that co-op work is one of the requirements for the degree.

The student benefits from seeing on his job the application of the theory he has learned in school. He gets to rub shoulders with workmen engaged in making a living. He learns their point of view, and above all he learns to get along with them. He respects discipline, matures rapidly, and is not afraid of responsibility. He proves his engineering aptitude by actual try-out. On the day after graduation, if he has been properly supervised, the co-op student hangs up his coat and hat and goes directly to work; no campus interviews, no invitations to "visit our plant at our expense to get better acquainted"; and the good student, the one who would get an offer from every interviewer, has something very tangible as a reference point when he evaluates all other offers. Then there is the by-product, wages. It is a fact that co-op wages, when there are no strikes or lay-offs, will pay the major part of any co-op's way through college. Nevertheless, the University emphasizes and tries to drive home the point that wages are secondary. It must be admitted, however, that probably many young men, whose economic status might otherwise prevent their attempting college work, can get an engineering education by the co-op method.

No specialized courses are taught at the University; only the basic fundamentals of the several branches of engineering education. The specialization comes on the co-op job. It would seem that the wood products industry could lay out a 96-week work program, starting with plant labor or maintenance helper, and including all the departments a co-op should be familiar with, for what the industry would consider an adequate background. If any wood products member should interest high school seniors in attending a co-op college, the co-op training at his plant could include lectures and demonstrations in problems peculiar to the wood products field. The college would furnish the fundamental theory.

There are at least two ways of producing wood products engineers and chemists; the summer experience method and the co-op system. Presented here were the essential features of the regular Co-operative Method, the so-called Schneider Plan; or to use the name that has come into general use, the Cincinnati Plan.



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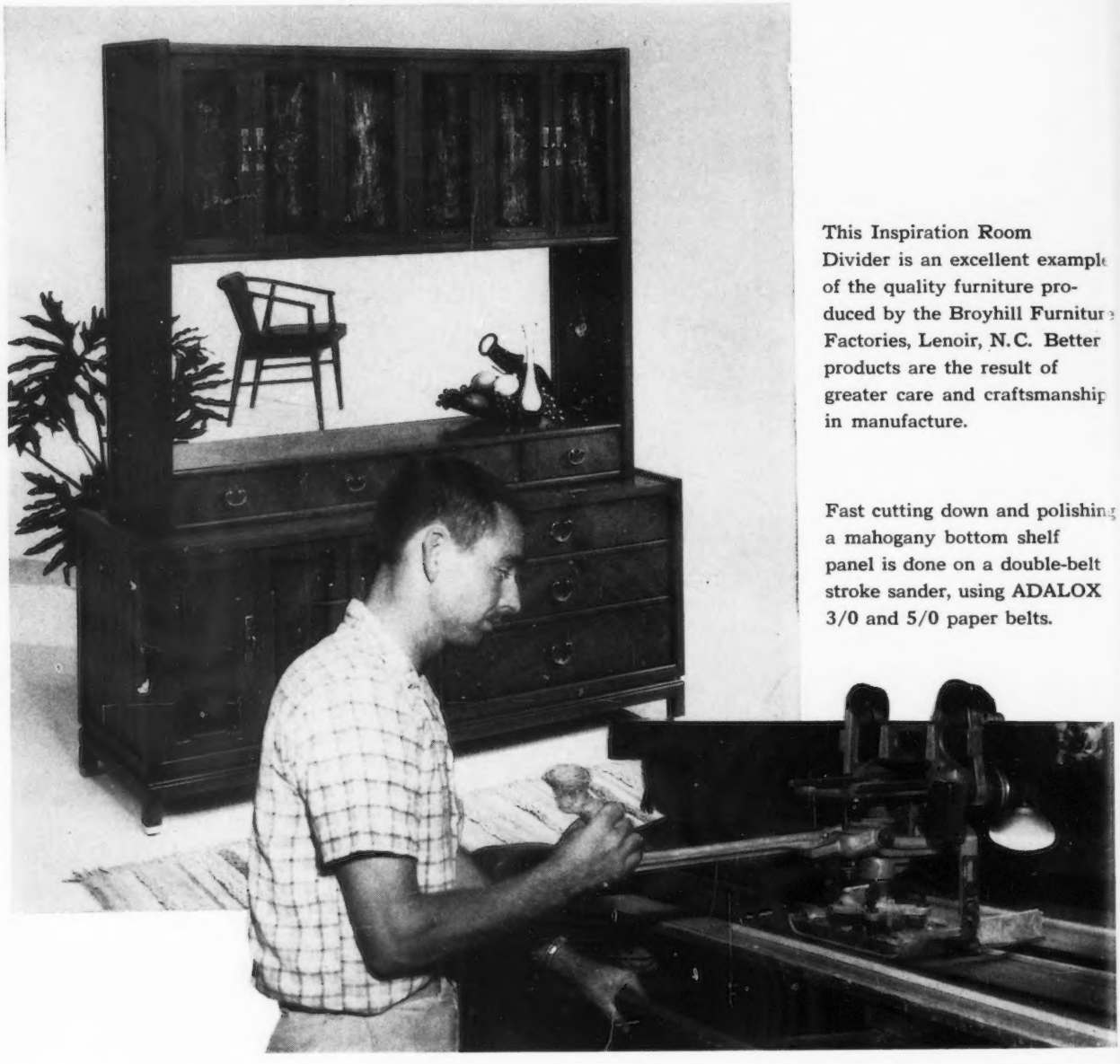

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